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THESIS

**SUCCESSIVE INTERFERENCE CANCELLATION
IN RAKE RECEIVERS FOR CDMA SIGNALS**

by

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June 2009

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The objective of this thesis is to investigate various techniques of Successive Intracell Interference Cancellation (SIIC) for Wideband-Code Division Multiple Access (W-CDMA). These techniques can improve the performance of CDMA interceptors and enhance the operation of cellular mobile communication systems.

The research focuses on the forward link (downlink) where orthogonal covering is employed. We examine three interference cancellation techniques that suppress the intracell multiuser interference. The first method is called subtraction, and the second method is called projection. We also examine a third method, which is a modification of the second method, and we call it modified projection method.

Although our receiver seems more complex compared to a conventional Rake receiver, it is shown to be effective in increasing the channel capacity.

Independently from the above study, we also demonstrate the performance of Walsh Index Detector (WID). This detector gives us the opportunity to detect the indexes that are being used in W-CDMA signals without prior knowledge of them.

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**SUCCESSIVE INTERFERENCE CANCELLATION
IN RAKE RECEIVERS FOR CDMA SIGNALS**

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ABSTRACT

The objective of this thesis is to investigate various techniques of Successive Intracell Interference Cancellation (SIIC) for Wideband-Code Division Multiple Access (W-CDMA). These techniques can improve the performance of CDMA interceptors and enhance the operation of cellular mobile communication systems.

The research focuses on the forward link (downlink) where orthogonal covering is employed. We examine three interference cancellation techniques that suppress the intracell multiuser interference. The first method is called *subtraction*, and the second method is called *projection*. We also examine a third method, which is a modification of the second method, and we call it *modified projection method*.

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EXECUTIVE SUMMARY

One of the most important applications of modern technology in 21st century that changed the way of communication between people is cellular mobile communications. Cellular subscribers have grown rapidly worldwide, and the continual demand for more and more alternative applications and services has led to the development of new and more efficient techniques.

The goal of all new techniques is to exploit the capacity of the existing and limited bandwidth in the most efficient way so more users can be served. An important limitation of the forward link is interference. In this research, we examine methods to alleviate the effect of interference.

The main point of our research is the performance of a modified Rake receiver that can select the most powerful signal and subtract it from the received signal using several methods. This reduces the effect of interference in weaker finger signals and enhances the performance of the receiver. We examine three interference cancellation techniques that suppress the intracell multiuser interference: *subtraction*, *projection* and we also examine a third method, which is a modification of the second method, and we call it *modified projection method*.

We found that it is worthwhile to use the projection method for more than 32 effective users to improve the communication system reliability. With that method we can achieve an improvement of 150% in channel capacity. We conclude that an adaptive system that employs the subtraction and the modified projection methods for up to 26 effective users and the projection method for more than 26 effective users can provide superior performance as compared to a system that adapts using only one method.

We also demonstrate the performance of Walsh Index Detector (WID). We conclude that this detector can gives us the opportunity to detect the indices that are being used in W-CDMA signals without prior knowledge of them.

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I dedicate this work to my son, Stavro Gkioka, for his continuous loving support and the happiness that he brings to my life.

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I.   INTRODUCTION

A.   OVERVIEW

Cellular communications have a vital role in modern technology and affect many aspects in everyday social and economic life. This is the reason for the development of new standards that provide better efficiency. This research is involved with third generation (3G) cellular standards.

Wideband-code division multiple access (W-CDMA) and Quadrature Phase-Shift Keying (QPSK) modulation support third generation cellular standards. All users can send their signals on the same carrier with the same or with different data rates depending on the kind of information.

A primary drawback to the above method for downlink transmission is interference. A multipath fading channel makes this problem more severe and decreases the capacity of the channel.

B.   THESIS OBJECTIVE

The target of our research is to examine different methods of demodulation based on alternative ways of processing the signal with the help of various algorithms. The main goal in the use of these algorithms is to cancel interference so as to improve the performance and the channel capacity.

An important drawback is that all methods require a receiver more complex than a conventional Rake receiver. There is a trade-off between complexity and channel capacity, but with the need for more capacity and the evolution of electronics and signal processors, it seems that the overall advantage of interference cancellation is worthwhile.

The main point of our research is the performance of an original modified Rake receiver that can select the most powerful signal and subtract it from the received signal using several methods. In our research instead of canceling out the stronger user one by one [1], we cancel out the stronger finger output from the signals of all users simultaneously.

Our research is based on the work of M. F. Madkour [1], who worked on algorithms in 2002, to cancel out Interference in CDMA signals. Based on his paper we create an original modified Rake receiver that doesn't search for the stronger signals, instead it consider that the stronger signals comes from the first finger of the Rake receiver.

The result of our original modified Rake receiver is the elimination of the interference of the stronger signals to the weaker signals. These actions improve the performance of the other fingers of the receiver and, as a result, decrease the bit error.

Due to the huge models that we create for modeling and testing the receiver we considered that wasn't useful to attach them in the thesis. All models are available from the author.

C.   THESIS SYNOPSIS

The structure of this thesis is organized into the introduction, background (Chapter II) and seven more chapters. Chapter III contains the performance of the Simulink model that we use for all our experiments. In Chapters IV, V, and VI, we demonstrate the performance of the three methods of successive cancellation that we examine. Chapter VII contains a comparison between cancellation methods. In Chapter VIII, we demonstrate the performance of Walsh Index Detector (WID). Finally, Chapter IX presents the conclusion based on the study discussed in previous chapters.

II.   BACKGROUND

In this chapter, we will demonstrate the basic background knowledge and principles needed for understanding W-CDMA and 3G cellular communications. Also, this background knowledge is necessary for understanding the way that our Simulink model works. All results in this research are from that model.

A.   CODE DIVISION MULTIPLE ACCESS

One of the most important limitations in modern digital communications is channel capacity. For this reason, many methods have been designed to target the usage of a channel in the most efficient way. For cellular communications the most relevant method is multiple access. This method allows us to transmit and receive information from different sources through the same channel. As a result, many users can communicate using the same channel. Some of the multiple access methods are Time-Division Multiple Access (TDMA), Frequency-Division Multiple Access (FDMA), and Code-Division Multiple Access (CDMA). There are two types of CDMA. The first is Frequency-Hopping (FH-CDMA), and the second is direct sequence (DS-CDMA). In this research, we examine only the second type. For simplicity we call it CDMA.

1.   Walsh Functions

Before we discuss Walsh functions it is necessary to mention that we can describe a bit in two ways. The first is with 0s and 1s, and the second is with 1s and -1s. In CDMA, we will use the second way for all description. We do that because it allows multiplication instead of logical operations, like modulo-2 addition, for the processing of CDMA. This is illustrated in Figure 1.

$$
\boxed{
\begin{array}{c}
\textbf{MAPPING} \\
0 \rightarrow 1 \\
1 \rightarrow -1
\end{array}
}
$$
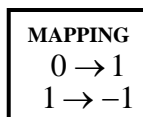
Figure 1.   Mapping.

We will start with the principles of Walsh functions because they are the basis of orthogonal CDMA. Walsh functions are based on the Hadamard matrix, which is a square matrix with 1s and -1s. For example, the 4x4 Hadamard matrix is produced as shown in Figure 2 [2].

$$H_1 = \begin{bmatrix} 1 \end{bmatrix}$$

$$H_2 = \begin{bmatrix} H_1 & H_1 \\ H_1 & -H_1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$H_4 = \begin{bmatrix} H_2 & H_2 \\ H_2 & -H_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

Figure 2.   Production of Walsh functions.

The main characteristic of a Hadamard matrix is that all the rows are mutually orthogonal. The advantage of an orthogonal matrix is that it allows the multiplexing of signals together.

The number of signals M that are used for spreading the information of the baseband signal is the same as the number of rows (index) or columns of the Hadamard matrix. In an abstract way, we can say that this number is the maximum possible Spread Factor (SF). We can also use part of the rows (multiples of two) to spread the signal, and in reality this is what we call Spread Factor, as will discussed further in subsequent sections.

To spread the information bit, we multiply the bit with one of the rows (indexes) of the matrix. In the same way we can spread many signals using different rows of the same matrix. Each row represents one user. Thus, every element of the multiplication defines one chip, and so there are M chips per bit with duration $T_c = T_b / M$, and the chip rate is $R_c = MR_b$, as illustrated in Figure 3.
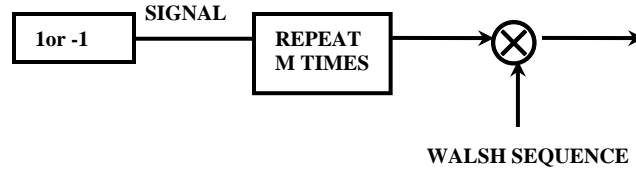
Figure 3.   Block diagram of spreading the signal with Walsh function.

The dispreading of the CDMA signal is achieved by multiplying the received signal with the appropriate Walsh sequence.

2.   Pseudo-Noise Sequence

Cellular communication is organized into cells. In the third generation every cell shares the same frequency bandwidth. So this raises a question, how can one base station separate its signals from an adjoining station? The answer lies with the use of a pseudo-noise (PN) sequence that produces a code unique for every cell. In this way, every station can separate its signals and multiple-access is enabled.

The field of PN sequences is broad, so we briefly present only the main idea on one of the most important codes, that is, maximal sequences or *m*-sequences [2].

The objective of a PN sequence is to produce a sequence of numbers, 1s and -1s (after mapping), in a specific and periodic way known only to the transmitter and the receiver. The encoding is achieved through the multiplication of the information signal with the elements of the PN-sequence. In this research, we consider the chip rate to be the same as the rate of PN generator, but there is no limitation in using multiple elements of PN generator to encode only one bit. In that situation, the bit period will be N times the period of the PN generator. Figure 4 shows the generation of a direct sequence Binary Phase-Shift Keying (BPSK) signal.
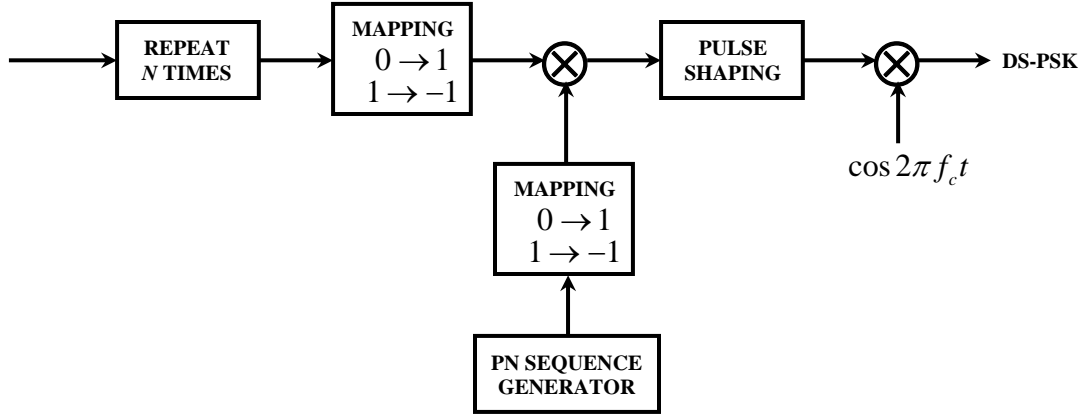
Figure 4.   Direct sequence, binary phase-shift keying (From: [2]).

3.   Spread Factor-Orthogonal Covering

The number of Walsh functions that we use for spreading the signal is the same as the number of rows M or columns of the Hadamard matrix. That is the maximum possible spread factor. Also we consider the chip period and the chip rate as duration $T_c = T_b / M$, and $R_c = MR_b$.

Each signal uses a Walsh function for spreading. There are two ways that all user signals can be spread. The first is by using the maximum possible spread factor for every user. Thus, all users will have the same spread factor.

The second way is to use variable length Walsh functions. Then every user will have its own spread factor. In that instance, we understand that every user will potentially spread a different number of bits in the same time. That happens because the chip rate is the same for all users, so users with double spread factor will have the half bit rate. In that instance a very important problem is created: the signals are not always orthogonal to each other unless the right set of Walsh functions is employed.

Consider two users with the same spread factor using the first and the third rows of a fourth order Hadamard matrix for spreading as in Figure 5. The first and third rows of this matrix are orthogonal. But if the second user has a spread factor of two instead of

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four, then it will use only the first two elements of the third row for spreading half of its bits. In that situation, the dot product is two, and the space is not orthogonal anymore.

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

Figure 5.   Hadamard matrix.

The advantage of an orthogonal space is that it gives the opportunity to multiplex all the signals together and separate them again. If we destroy orthogonality between users, we destroy the multiplexed signal, and consequently, we can not extract the individual user data.

Instead of using the third row in the above example, we could use the second row. Then the two signals are orthogonal despite the fact that they use different spread factors. For the above reasons, we review variable orthogonal covering techniques for applications with different spread factors for different user channels as shown in Figure 6 [2].
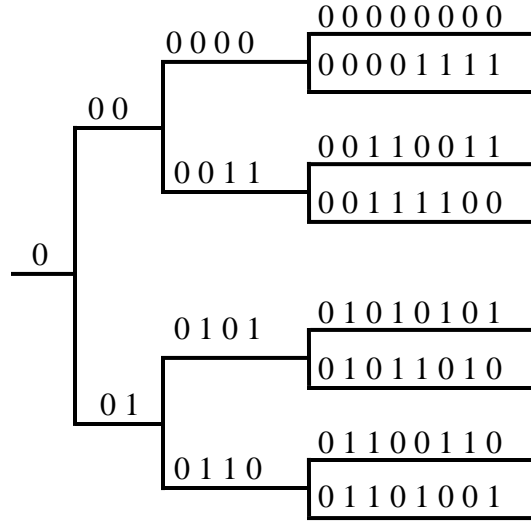
Figure 6.   Variable length orthogonal sequences before mapping.
(From: [2]).

The following steps are used to create the tree in Figure 6. First, we start with binary 0 and move to the right by doubling the length of the sequence. On the upper branch we repeat the left data ones and on the lower branch we repeat their complement. The above tree shows binary data before mapping. Now, by using variable length sequences from different mother branches, we protect the orthogonality of our multiplexed signal. The tree in Figure 6 also explains the reason why we use only multiples of two to spread signals. Finally, we can scale any row by multiplying it with an integer number without violating orthogonality [2].

4.   Summary

Based on the above introductory materials, we can demonstrate in Figure 7 how direct sequence code division multiple access works.

USER CHANNEL 1

$\{0,1\}$ → **REPEAT M TIMES** → ⊕ → **REPEAT N TIMES** → ⊕ → **MAPPING $0 \rightarrow 1$ $1 \rightarrow -1$** → Σ → **PULSE SHAPE** → ⊗ →

$\{0,1\}$
WALSH SEQUENCE 1

$\{0,1\}$
PN SEQUENCE

$\cos 2\pi f_c t$

USER CHANNEL M →
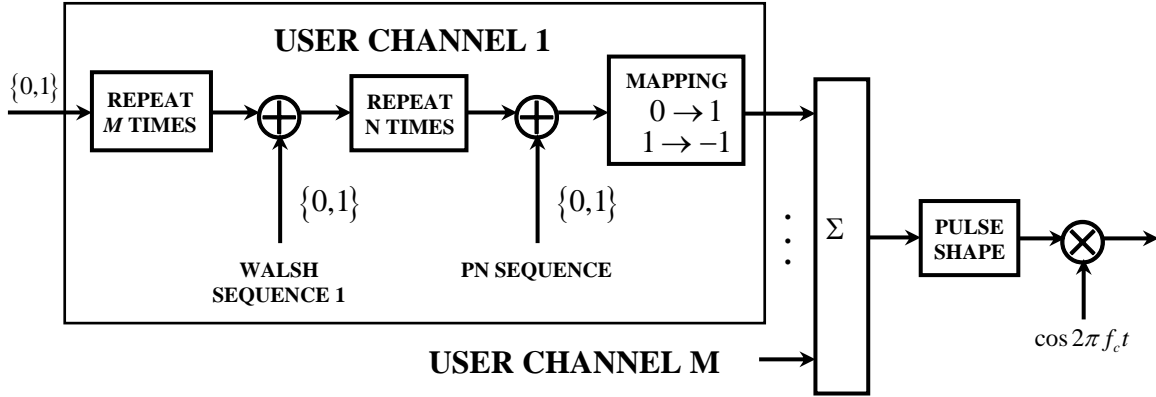
Figure 7.   Walsh orthogonal covering (From: [2]).

For Quadrature Spreading, as shown in Figure 8, we can use two different PN sequences, one for the I-channel and another one for the Q-channel. The advantage of this method is to provide phase synchronization at the receiver [2].

USER CHANNEL 1

PN$_I$ SEQUENCE
$\{0,1\}$

REPEAT M TIMES → ⊕ → **REPEAT N TIMES**

⊕ → **MAPPING $0 \rightarrow 1$ $1 \rightarrow -1$** **I** → Σ → **PULSE SHAPE** → ⊗

⊕ → **MAPPING $0 \rightarrow 1$ $1 \rightarrow -1$** **Q** → Σ → **PULSE SHAPE** → ⊗

$\{0,1\}$
WALSH SEQUENCE 1

$\{0,1\}$
PN$_Q$ SEQUENCE

$\cos 2\pi f_c t$

Σ

$-\sin 2\pi f_c t$

USER CHANNEL M
I
Q
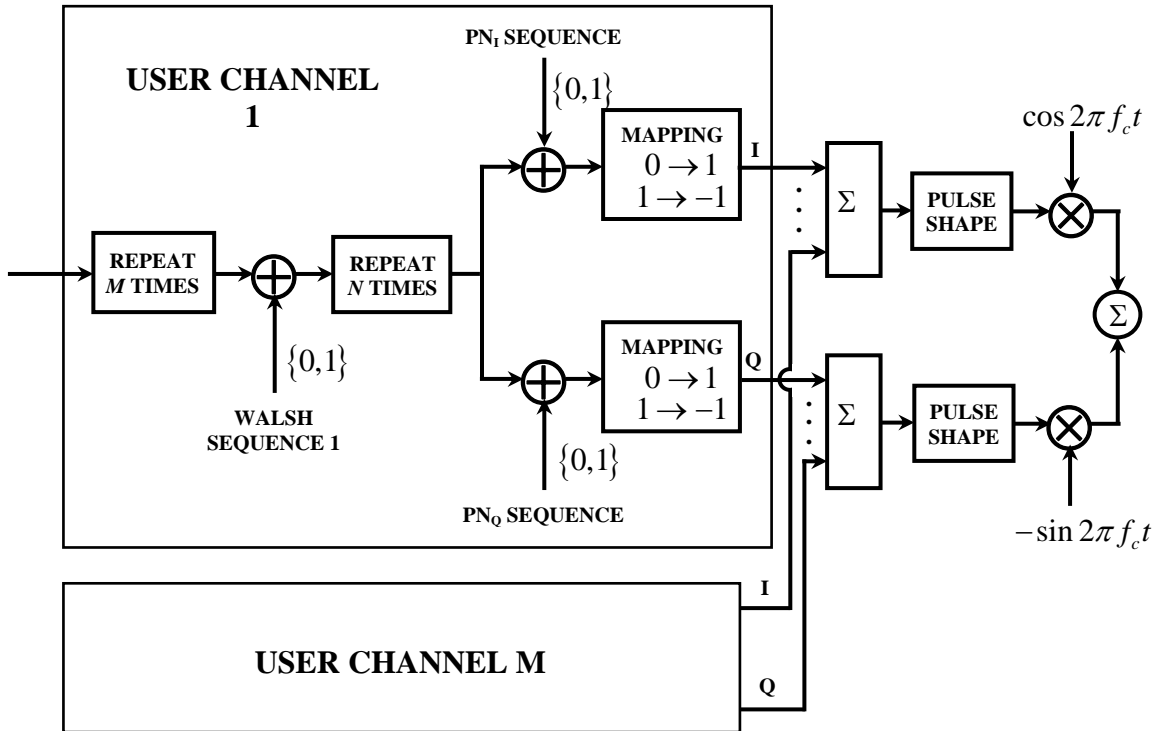
Figure 8.   Quadrature orthogonal covering (From: [2]).

B. FADING CHANNEL

One of the most important revolutions in the 20th century was modeling. With that tool science can save time, money and make experiments without the fear of failure. In many applications in communications, we model the channel as an Additive White Gaussian Noise (AWGN) Channel. In mobile wireless communications, the AWGN channel alone does not reflect reality.

For mobile wireless communications, the signal is influenced mainly by three factors: reflection, diffraction, and scattering. Reflection is caused by large objects like hills, buildings, and other large structures. Diffraction is caused by the signal sliding along or beading around building corners. Scattering is caused by the signal reflecting via small objects like trees, vehicles, pillars and so on. Those processes cause the transmitted signal to be received at the receiver via multipath delayed replicas. This results in signal fading [2].

Figure 9 shows the bit error probability of BPSK for both the non-fading channel and a Rayleigh fading channel. It shows that the performance in a Rayleigh fading channel is much worse than that for a non-fading channel.
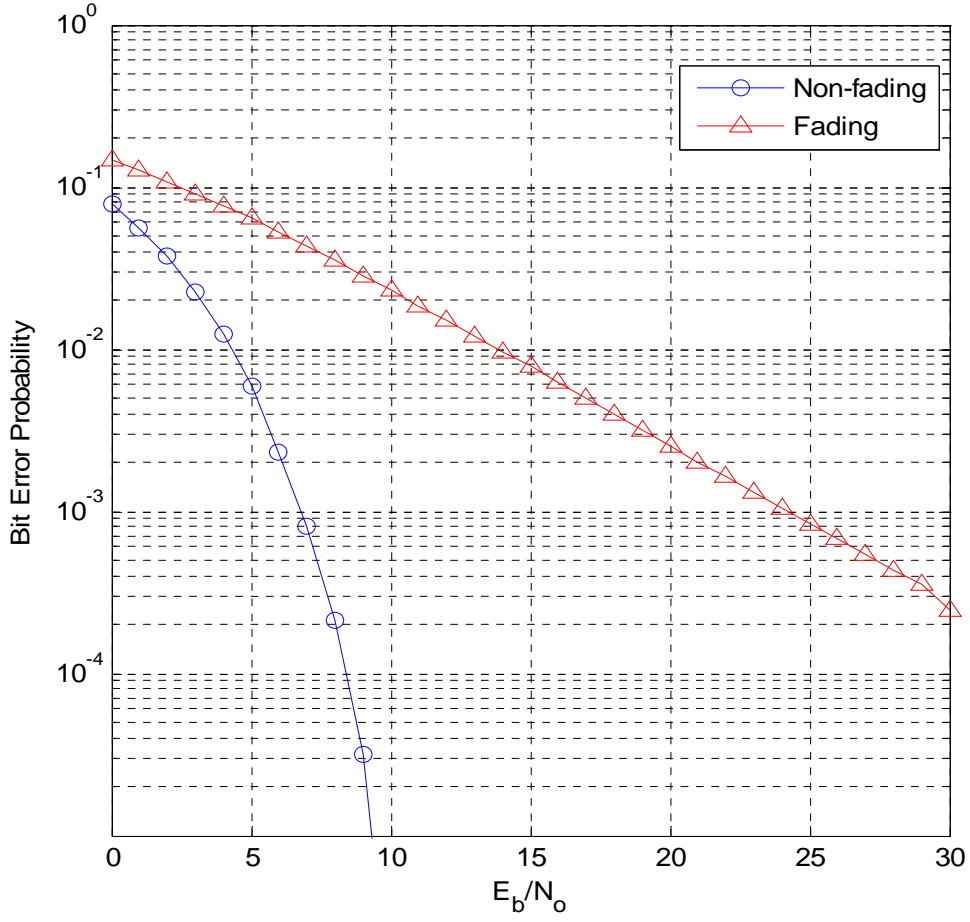
Figure 9.   Comparison of fading and non-fading channels for BPSK.

C.   RAKE RECEIVER

In this section, we briefly describe the Rake receiver (Figure 10). As already described in section B, in a fading channel we receive replicas of the same signal with different powers and delays. The main goal of a Rake receiver is to process the fading signal and take advantage of the replicas that follow different paths. For that reason, a Rake receiver uses different fingers, where each finger processes a replica separately and combines the replicas together. This combining technique decreases the bit error rate and increases the reliability of the receiver.

The Rake receiver consists of finger processors, a maximal ratio combiner (MRC) and a detector. Every finger has its own processor. The main purpose of the processor is to combine all the output chips for one bit and give an output for that specific bit. After that, all the finger outputs feed the MRC that combines the signals. Each finger works as a tap. A bigger weight is given to the finger with a stronger signal. The detector determines which bit was transmitted.
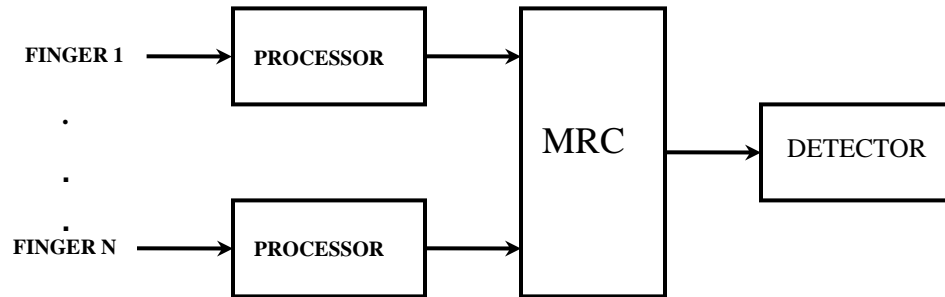
Figure 10.   Concept of a Rake receiver.

In Figure 11, with the help of Simulink, we present the bit error probabilities of two different techniques for transmission over a Rayleigh fading channel. The first curve is the bit error probability of a conventional BPSK receiver and the second is the bit error probability of a Rake receiver using QPSK-CDMA modulation for only one user. The improvement in the bit error probability using a Rake receiver is obvious.
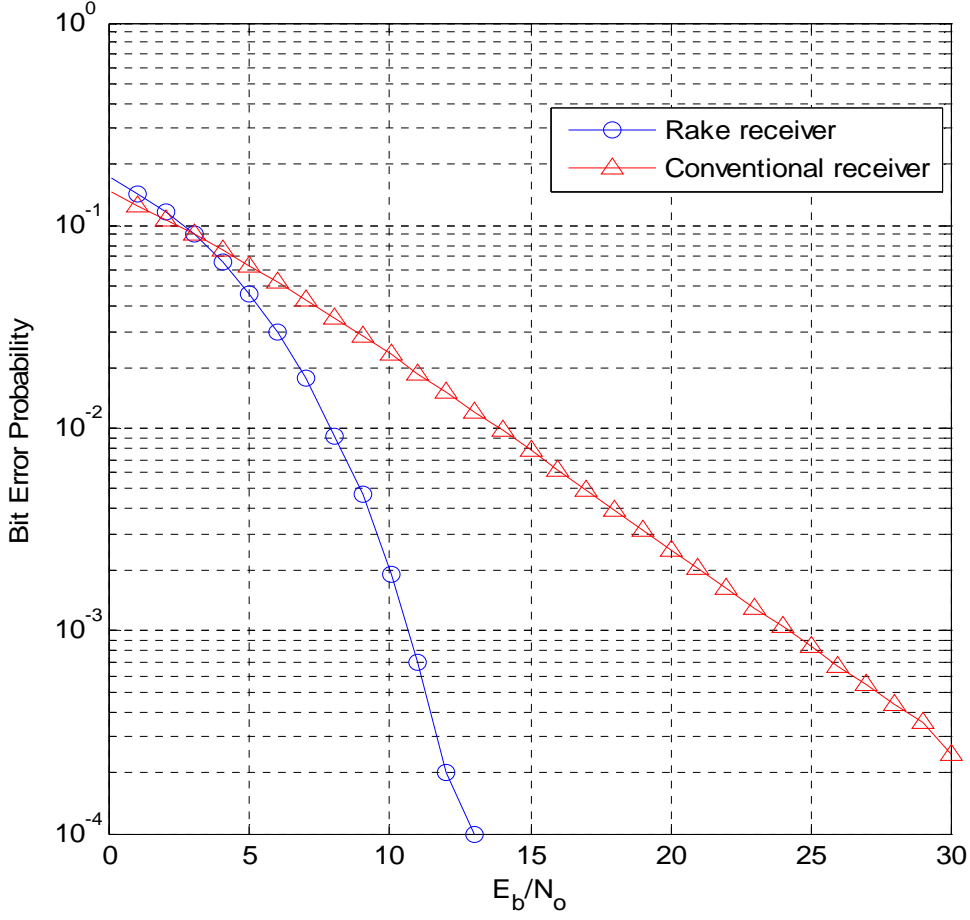
Figure 11. Comparison of bit error probabilities of a Rake receiver for QPSK-CDMA-one user signal with conventional BPSK receiver in a Rayleigh fading channel.

D. SIGNAL MODEL

In this section, we represent the signal before and after its transmission through a fading channel. We consider the transmitted symbol $\boldsymbol{d}_k = d_k + j\hat{d}_k$, $kT_s \le t < (k+1)T_s$, of a complex spreading I-Q signal (QAM, MPSK) where d_k and $\hat{d}_k$ are the kth in-phase and quadrature bits normalized to the smallest symbol energy $E = A^2 T_s/2$, respectively. We consider that we upconvert the signal to the carrier frequency f_c which is an integer multiple of $1/T_s$. The transmitted signal $s(t)$ is given by

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$$s(t) = \mathrm{Re}\left[s_L(t) e^{j2\pi f_c t} \right].$$

(2.1)

The complex envelope $s_L(t)$ is given by

$$s_L(t) = \boldsymbol{d}_k \boldsymbol{c}(t - kT_s).$$

(2.2)

The signal $\boldsymbol{c}(t)$ is the complex spreading PN sequence with unit amplitude squared pulse shape with chip time T_c and period NT_c.

The wideband channel impulse response is modeled as an *L*-tap channel with slow variations so that the channel taps remain constant over many symbols. The delays of each tap are $\tau_0(t) < \tau_1(t) < ... < \tau_{L-1}(t)$. We assume that the multipath delays are less than a symbol time so that the channel is time-invariant. The channel response can be expressed as follows:

$$h(\tau,t) = \sum_{l=0}^{L-1} h_i(t)\delta(t - \tau_i(t)).$$

(2.3)

The received complex signal $r_L(t)$ is equal to the transmitted signal $s_L(t)$ convolved with channel response $h(t)$ and is equal to:

$$r_L(t) = A\sum_{l=0}^{L-1} h_l \boldsymbol{d}_k\, e^{-j2\pi f_c \tau_l} \boldsymbol{c}(t - kT_s - \tau_l).$$

(2.4)

Equation (2.4) represents an ideal transmission. In practice the receiving signal has the form of

$$r_L(t) = A\sum_{l=0}^{L-1} h_l \boldsymbol{d}_k\, e^{-j2\pi f_c \tau_l} \boldsymbol{c}(t - kT_s - \tau_l) + I_{k-1}(t) + I_{k+1}(t) + n(t).$$

(2.5)

The term $n(t)$ represents AWGN with power spectral density $N_0/2$ (W/Hz). The terms $I_{k-1}(t)$ and $I_{k+1}(t)$ represent $L-1$ Intracell Symbol Interference (ISI) signals from the preceding $(k-1)^{th}$ symbol and from the succeeding symbol $(k+1)^{th}$, respectively [2].

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We assume perfect channel estimation so that the channel taps $h_l s$ and path delays $\tau_l s$ are known. Via L complex local carriers $\sqrt{2/T_s}\, e^{-j2\pi f_c(t-\tau_l)}$, $l=1,2,...,L$, we demodulate the received signal $r(t) = \mathrm{Re}\left[r_L(t)\, e^{j2\pi f_c t} \right]$ to L complex basebands, for each of the L paths. The next step is the complex dispreading process. We multiply the complex basebands with $\boldsymbol{c}^*(t-kT_s-\tau_l)/2$, $l=1,2,...,L$, (where $|\boldsymbol{c}(t)|^2 = 2$) so as to recover the specified symbol. Then we integrate the demodulated basebands for one symbol time to extract L pre-combining decision variables. This process constructs L Rake fingers. The output of the lth Rake finger for the kth symbol is given as Y_l where s_k is the unnormalized k^{th} symbol with energy $E_k = |s_k|^2$: [2]

$$
\begin{aligned}
Y_l &= \int_{kT_s-\tau_l}^{(k+1)T_s-\tau_l} A\sqrt{\frac{1}{2T_s}}\, h_l \boldsymbol{d}_k\, dt + I_l + I_l^- + I_l^+ + N_l \\
&= h_l s_k + I_l + I_l^- + I_l^+ + N_l
\end{aligned}
\qquad (2.6)
$$

Also $s_k = \sqrt{\dfrac{A^2 T_s}{2}}\boldsymbol{d}_k = \sqrt{E}\boldsymbol{d}_k$ and $E_k = |s_k|^2 = E|\boldsymbol{d}_k|^2$, where E is equal to smallest symbol energy $E = A^2 T_s/2$. The self-interference I_l is referred to as intrapath interference (IPI), and I_l^- and I_l^+ are ISI. The three interferences combined with Gaussian noise is denoted as $\mathcal{N}_l = I_l + I_l^- + I_l^+ + N_l$ and the L Rake finger outputs for the kth symbol are:

$$
Y_l = h_l s_k + \mathcal{N}_l,\ \ l=1,2,...,L.
\qquad (2.7)
$$

Figure 12 summarizes the Rake receiver model.

Integrator

$$\frac{h_1^*}{|h_1|}e^{-j2\pi f_c(t-\tau_1)} \quad \boldsymbol{c}^*(t-\tau_1)$$

MRC

Detector

Symbol-Bit Converter

Integrator

$$\frac{h_L^*}{|h_L|}e^{-j2\pi f_c(t-\tau_L)} \quad \boldsymbol{c}^*(t-\tau_L)$$
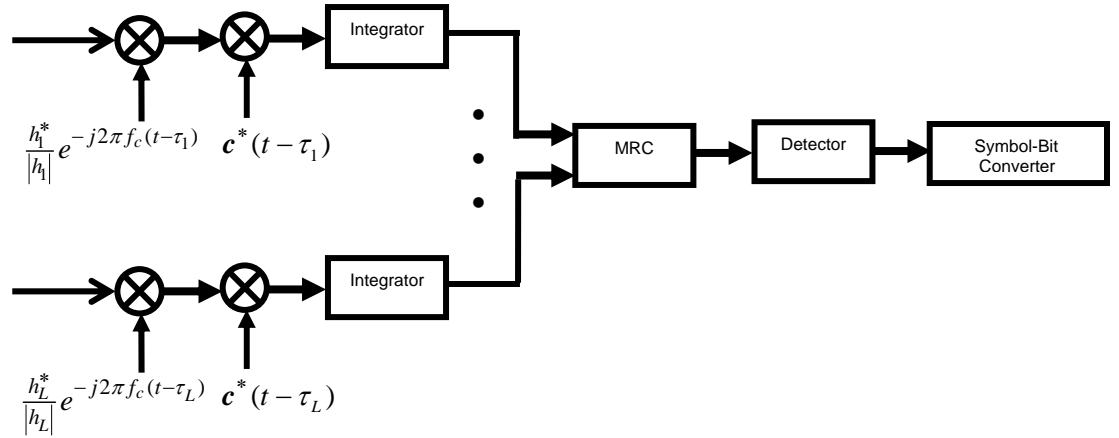
Figure 12.   Rake receiver (From: [2]).

In this chapter we discussed the background knowledge necessary to understand the main subject of the research. In the next chapter we will discuss the Simulink model that is used for all simulation results presented in this thesis.

III.   PERFORMANCE OF SIMULINK MODEL

In our experiments we use Simulink models to simulate the performance of Rake receivers in a fading environment. We construct three different Simulink models to examine three interference cancellation techniques that suppress the intracell multiuser interference and improve the communication system performance.

A.   NO CANCELLATION

Our purpose is to examine different cancellations techniques and make comparisons of their performance to the no cancellation model.
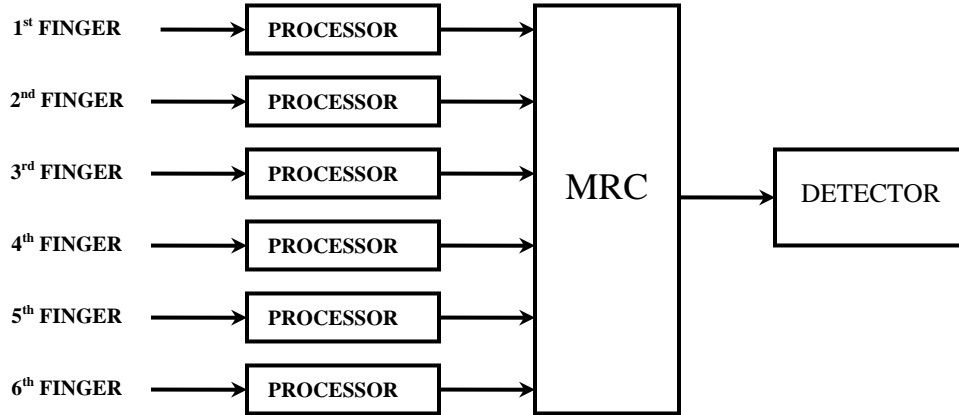
Figure 13.   No cancellation model.

Figure 13 illustrates the no cancellation model with six fingers having the following powers and delays: first finger, 0 dB, $0\,\mu s$; second finger, -1 dB, $0.4\,\mu s$; third finger, -9 dB, $0.8\,\mu s$; forth finger, -10 dB, $1.2\,\mu s$; fifth finger, -15 dB, $1.6\,\mu s$; and sixth finger, -20 dB, $2\,\mu s$. We assume complete synchronization between the fingers and the multipath channels. We also model the intercell multiuser interference as Gaussian noise, and we

assume QPSK modulation. The model used in this thesis is similar to the one used in [1] and is a reasonable representation for the mobile fading channel.

As we have already described, one user may have a spread factor that is a multiple of two. Now, we will introduce a new term, the effective spreading factor [1]. In our model we assume users with spread factors ranging from 8 (data) to 128 (voice). We consider a user with spread factor 128 as one effective user, a user with spread factor 64 as two effective users, and so on, until a user with spread factor 8 is 16 effective users. This happens because the users with small spread factor have high bit rates. As a result, they cause equivalent interference as if they were many users in the same system.

In our model, we use several combinations of users to carry out the experiments. For the model of 52 effective users, we actually use 7 real users as follows: two real users with spread factor 128 (2 effective users), one real user with spread factor 64 (2 effective users), two real users with spread factor 16 (16 effective users), and two real users with spread factor 8 (32 effective users). The sum of all the above effective users is 52.

In Figure 14, with the help of Simulink, we observe the bit error probability for 1, 12, 26, 32, and 52 effective users for the downlink through the specified Rayleigh fading channel with a conventional Rake receiver that does not use any cancellation techniques.
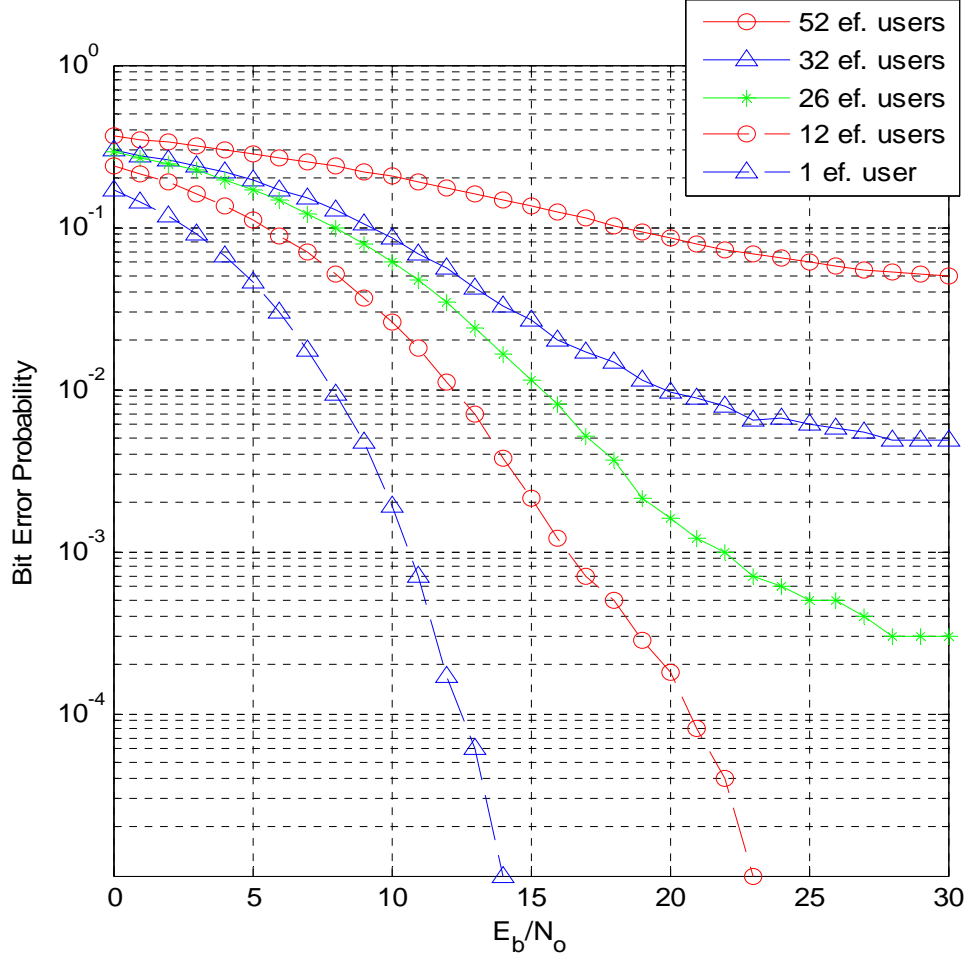
Figure 14.   Bit error probability for different numbers of effective users with no cancellation.

B.   CANCELLATION

In this section, we outline three methods of Successive Intracell Interference Cancellation (SIIC) for Wideband Code-Division Multiple Access (W-CDMA), which will be discussed in more detail in the subsequent chapters. The basic idea is to cancel the stronger signal. These methods improve the processing for weaker signals, hence, decreasing interference and enabling the receiver to perform better. In our models we regenerate and cancel out the stronger finger output from the signals of all users simultaneously. After cancellation the remaining finger outputs receive the modified

received signal that does not contain the strongest signal from the first figure [1]. Figure 15 shows a block diagram of interference cancellation in a Rake receiver.
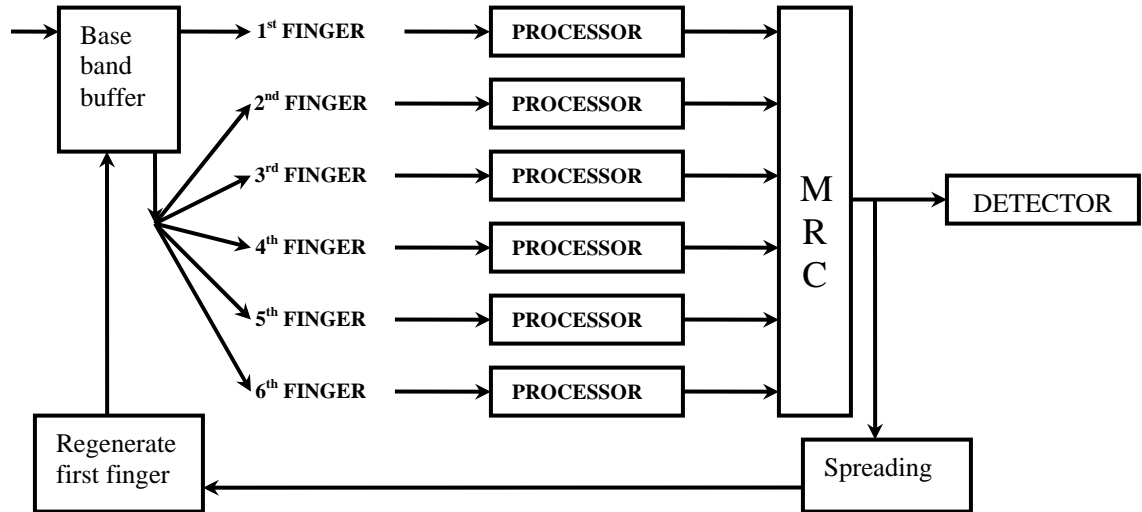

Figure 15.   Block diagram of Rake receiver with interference cancellation.

We continue the cancellation one-by-one to the other fingers, but the results are worse as we can see in the Figure 16. One explanation is that we over cancel the received signal. For that reason, in all experiments we cancel only the first (the stronger finger) from the overall received signal.
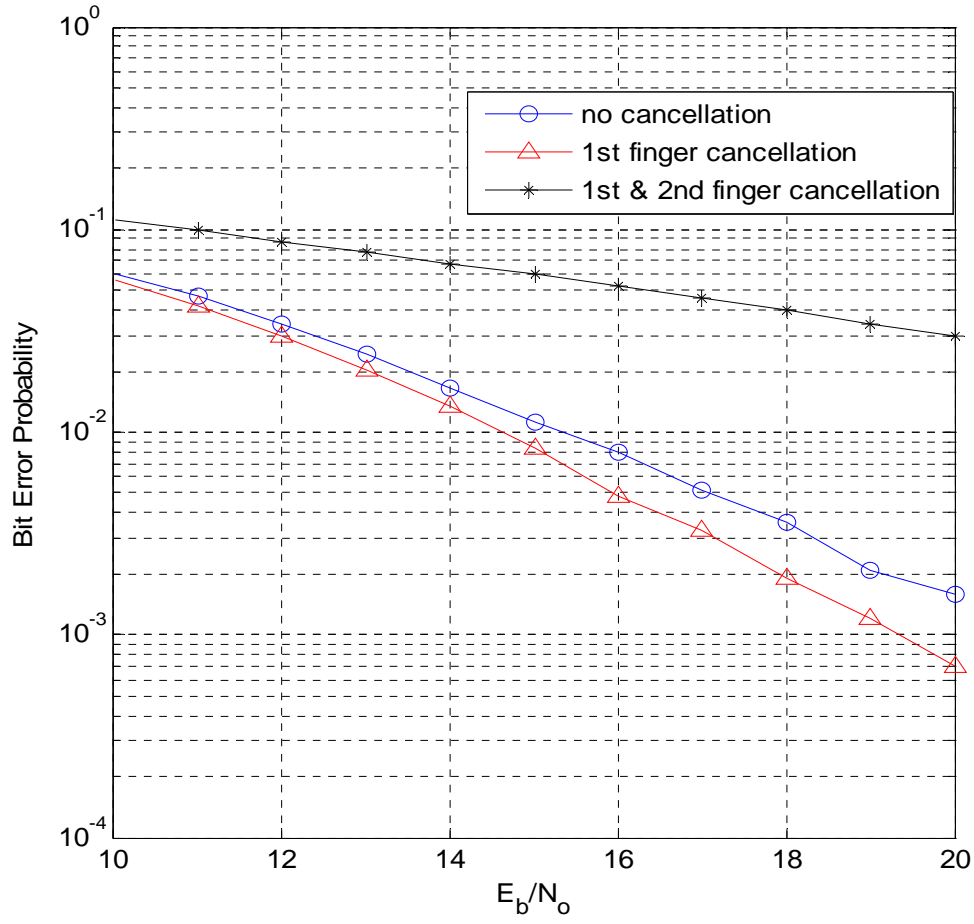
Figure 16.   Cancellation of the first finger and first and second fingers for 26 effective users.

C.   CHAPTER SUMMARY

In the next three chapters, we will demonstrate three different ways of cancellation and compare the results with the performance of the same system with no cancellation. In all methods we have better results, but there is a trade off with the complexity of the receivers when we process the signal twice.

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IV. PERFORMANCE ANALYSIS OF CANCELLATION WITH SUBTRACTION METHOD

Cancellation with subtraction is the simplest method compared to the other two methods considered in this thesis. The only action is to subtract mathematically the stronger, regenerated signal of first finger from the received signal as outlined in the previous chapter [1]. In the subsequent paragraphs we demonstrate the results for different numbers of effective users and compare the performance of this receiver with a conventional Rake receiver.

A. FOR 12 EFFECTIVE USERS

The performance both with and without cancellation for 12 effective users is shown in Figure 17. As can be seen, the improvement is about 2 dB when the bit error probability is smaller than $5x10^{-4}$.

Figure 17. Cancellation with subtraction method for 12 effective users.

B. FOR 26 EFFECTIVE USERS

The performance both with and without cancellation for 26 effective users is shown in Figure 18. As can be seen, the relative improvement is about 1 dB for $P_b < 8 \times 10^{-3}$, but the absolute performance is seriously degraded compared to 12 effective users. For example, when $E_b / N_o = 18$ dB, $P_b = 2 \times 10^{-4}$ and $P_b = 2 \times 10^{-3}$ when there are 12 and 26 effective users, respectively. So as the number of effective users increases, not only does the relative improvement due to cancellation decrease, but the absolute performance also decreases. As will be seen in the following sections, this trend continues as the number of effective users increases.
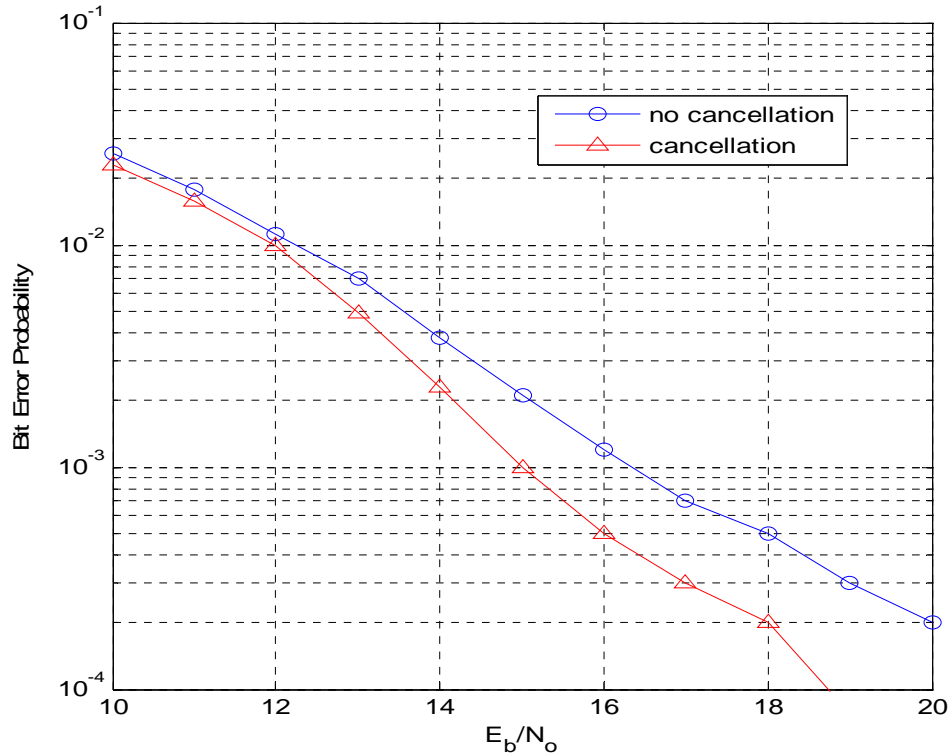

Figure 18.   Cancellation with subtraction method for 26 effective users.

C.   FOR 32 EFFECTIVE USERS

The performance both with and without cancellation for 32 effective users is shown in Figure 19. As can be seen, the improvement is about 2 dB at $P_b=10^{-2}$, but the absolute performance is seriously degraded compared to 12 or 26 effective users.
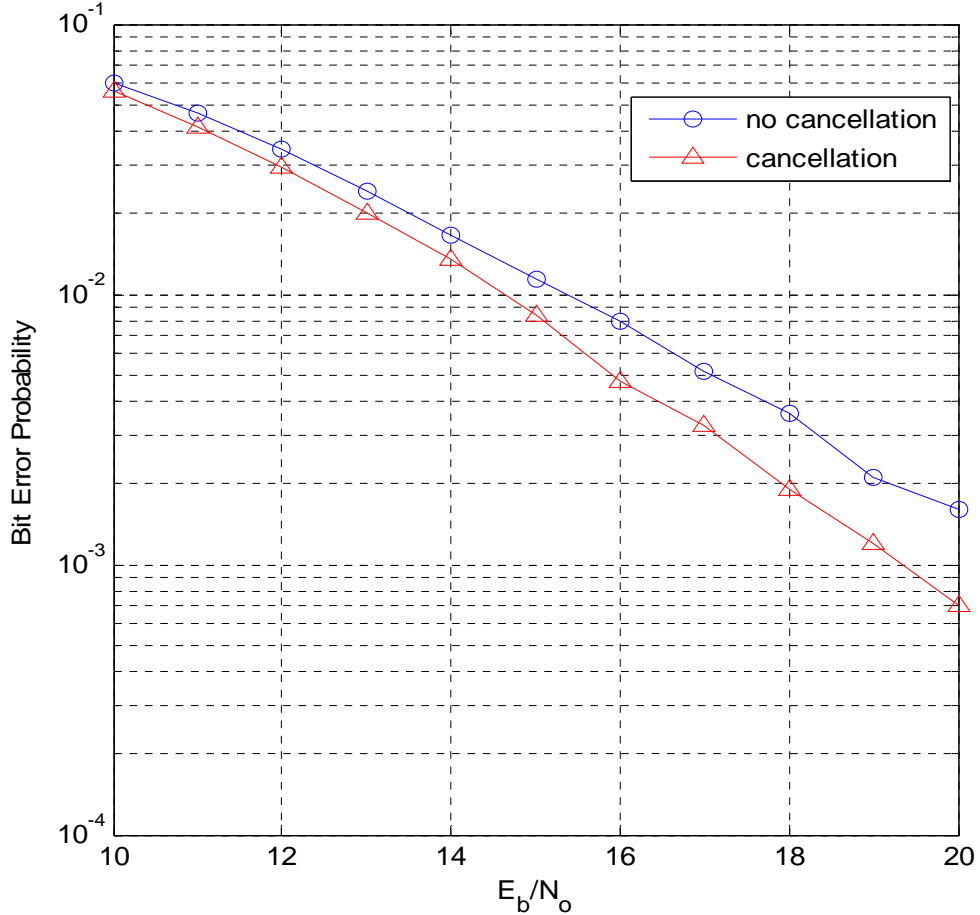

Figure 19.   Cancellation with subtraction method for 32 effective users.

D.   FOR 52 EFFECTIVE USERS

The performance both with and without cancellation for 52 effective users is shown in Figure 20. As can be seen, there is almost no improvement in this case.

Figure 20.   Cancellation with subtraction method for 52 effective users.

E.   CHAPTER SUMMARY

The subtraction method is effective only for less than 32 effective users. When the number of effective users exceeds thirty-two, the improvement is small.

In the next chapter, we will examine the performance of the cancellation with projection method.

V.   PERFORMANCE ANALYSIS OF CANCELLATION WITH PROJECTION METHOD

The cancellation method with projection is more complex than the subtraction method. The main point of cancellation with projection is not only to subtract the regenerated signal of first finger $\beta(t)$, so as to have a better performance for the remaining fingers, but also to cancel out its interference from the remaining fingers. This is achieved with the help of linear algebra and the characteristics of orthogonal space.

In the projection method, we project the received signal $\alpha(t)$ onto the orthogonal direction to the regenerated signal of the first finger $\beta(t)$ [1]. The remaining fingers receive the signal $\gamma(t)$ as follows:

$$\gamma(t) = \alpha(t) - \frac{\langle \alpha(t), \beta(t) \rangle}{\langle \beta(t), \beta(t) \rangle} \bullet \beta(t) \tag{5.1}$$

where $\langle \alpha, \beta \rangle$ is the inner product of α and β.

In the next paragraph, we show the results for the projection method for different number of effective users, 12, 23, 32, and 52, and compare the performance of our receiver with a conversional Rake receiver that does not use any cancellation techniques.

A.   FOR 12 EFFECTIVE USERS

The performance both with and without cancellation for 12 effective users is shown in Figure 21. As can be seen, there is almost no improvement for E_b / N_o less than 18 dB.
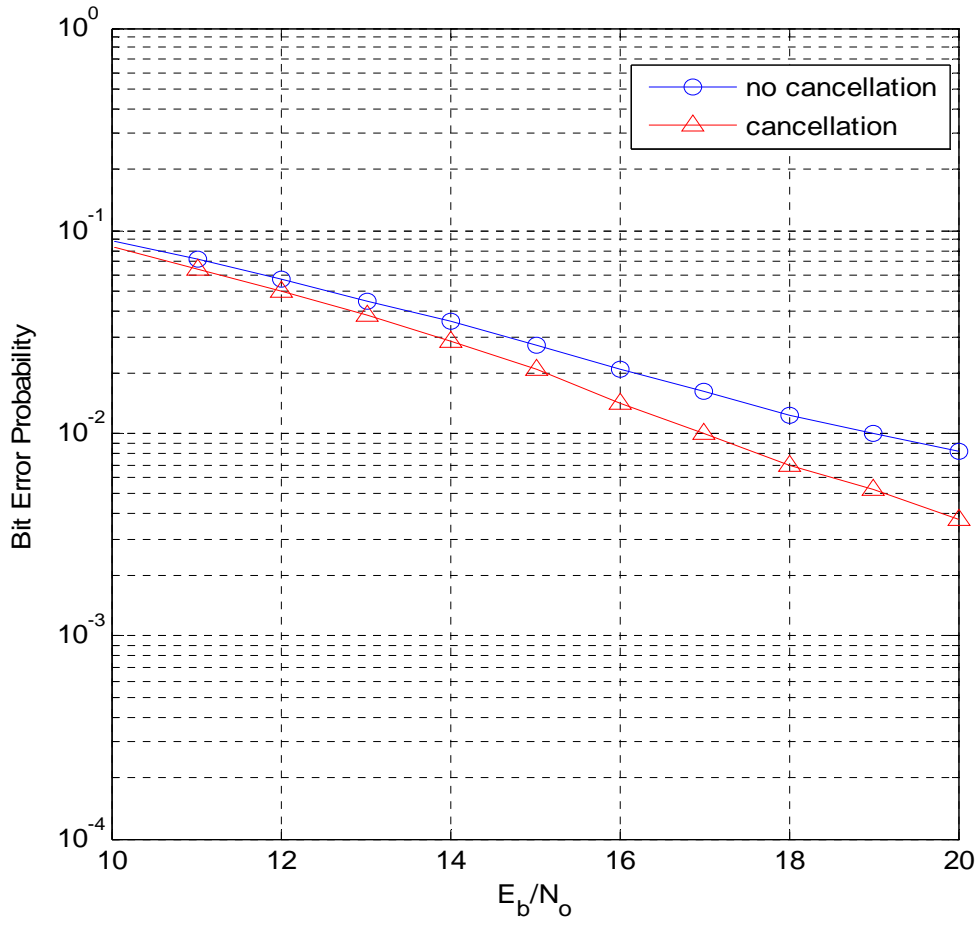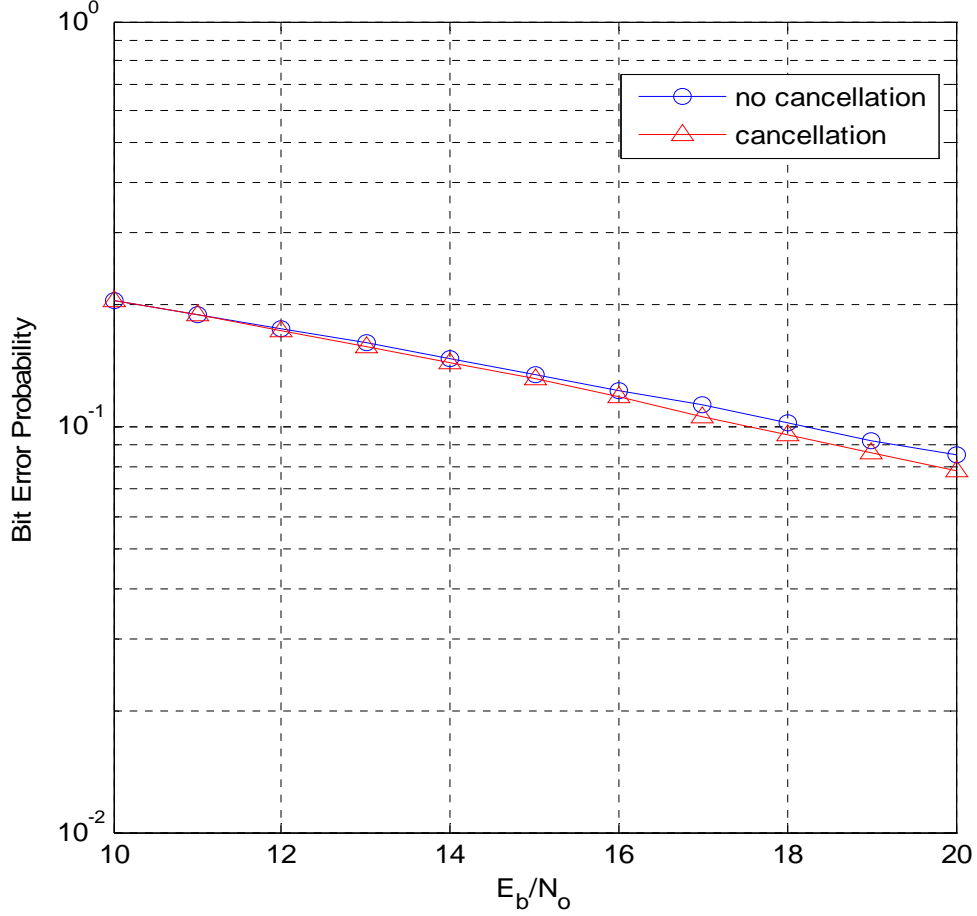

Figure 21.   Cancellation with projection method for 12 effective users.

B.   FOR 26 EFFECTIVE USERS

The performance both with and without cancellation for 26 effective users is shown in Figure 22. As can be seen, there is again almost no improvement.

Figure 22.   Cancellation with projection method for 26 effective users.

C.   FOR 32 EFFECTIVE USERS

The performance both with and without cancellation for 32 effective users is shown in Figure 23. As can be seen, the improvement is about 4 dB for $P_b = 10^{-2}$.
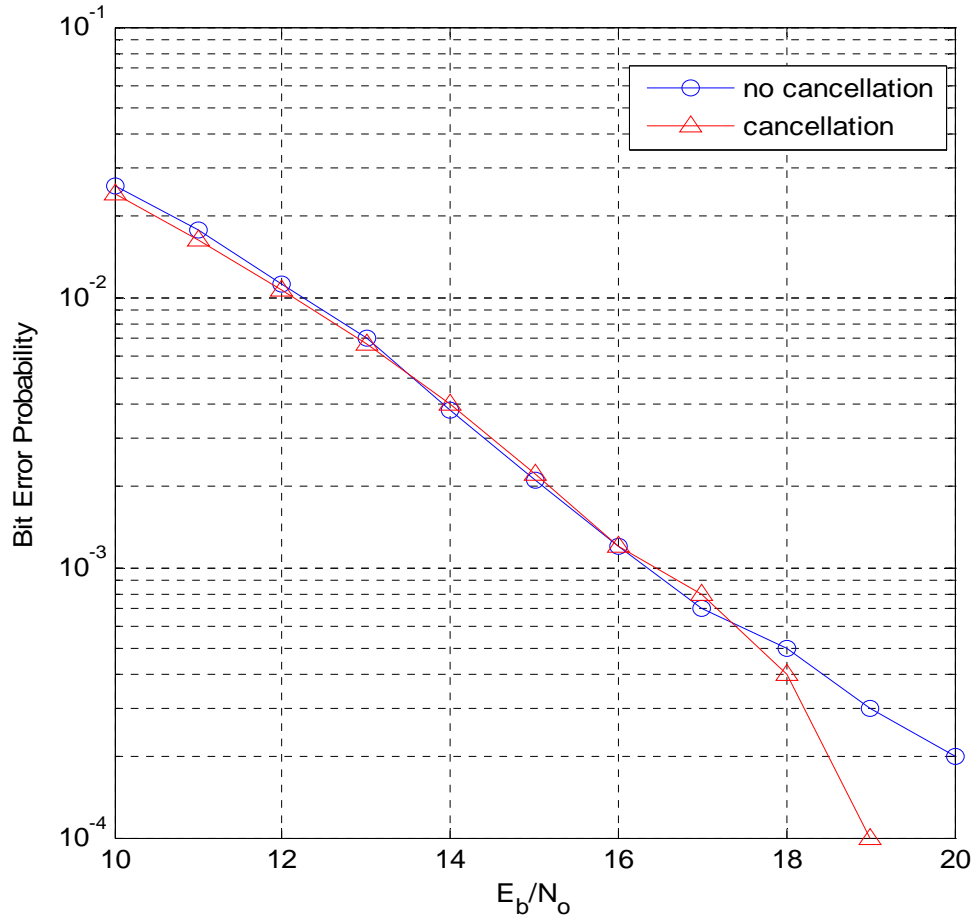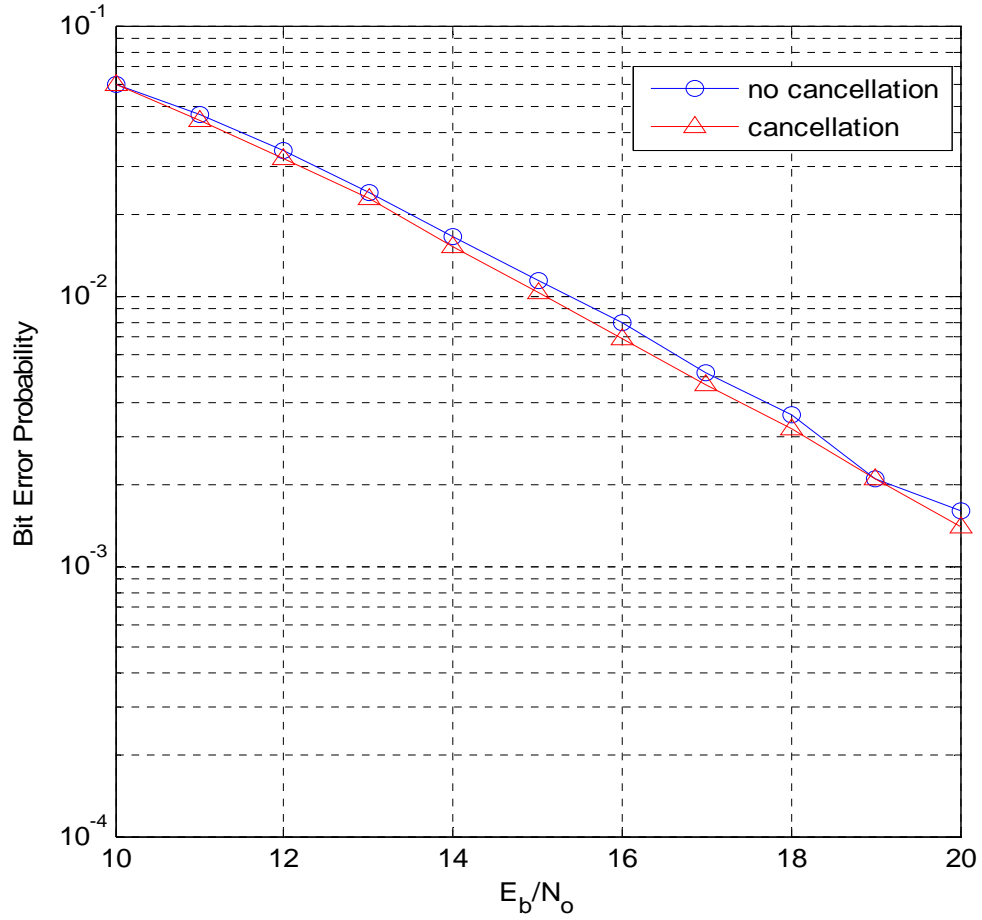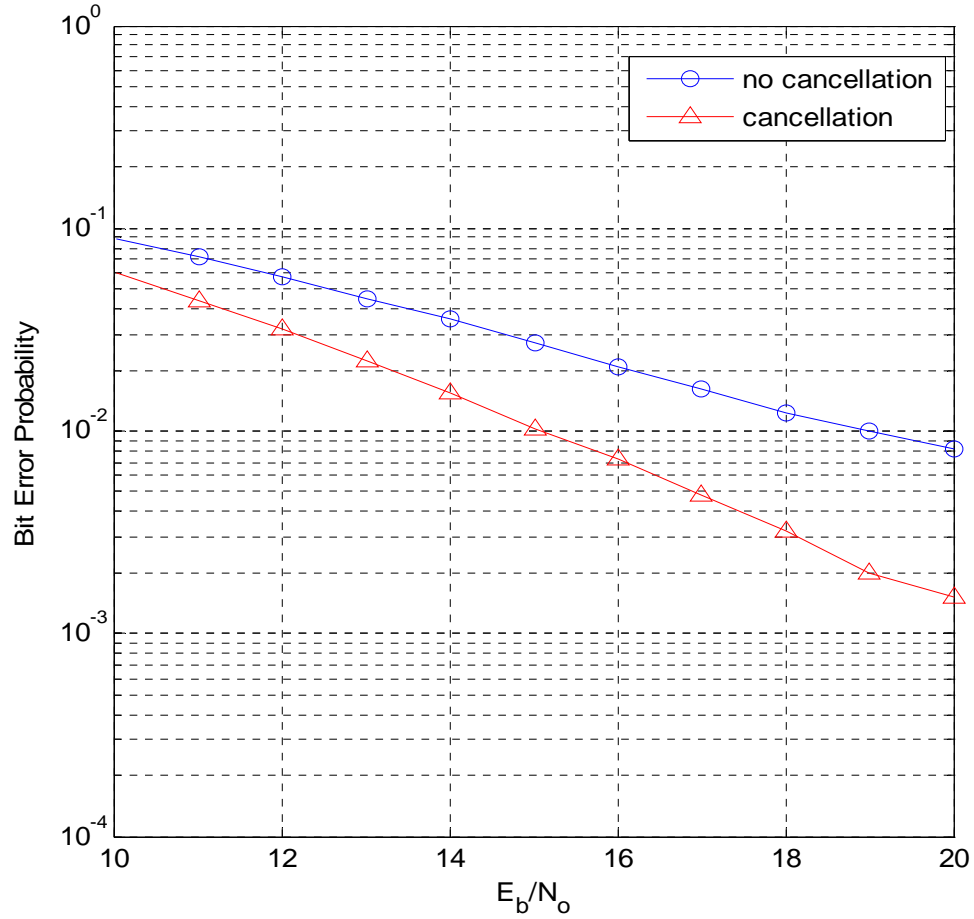

Figure 23.   Cancellation with projection method for 32 effective users.

D. FOR 52 EFFECTIVE USERS

The performance both with and without cancellation for 52 effective users is shown in Figure 24. As can be seen, the improvement is significant.
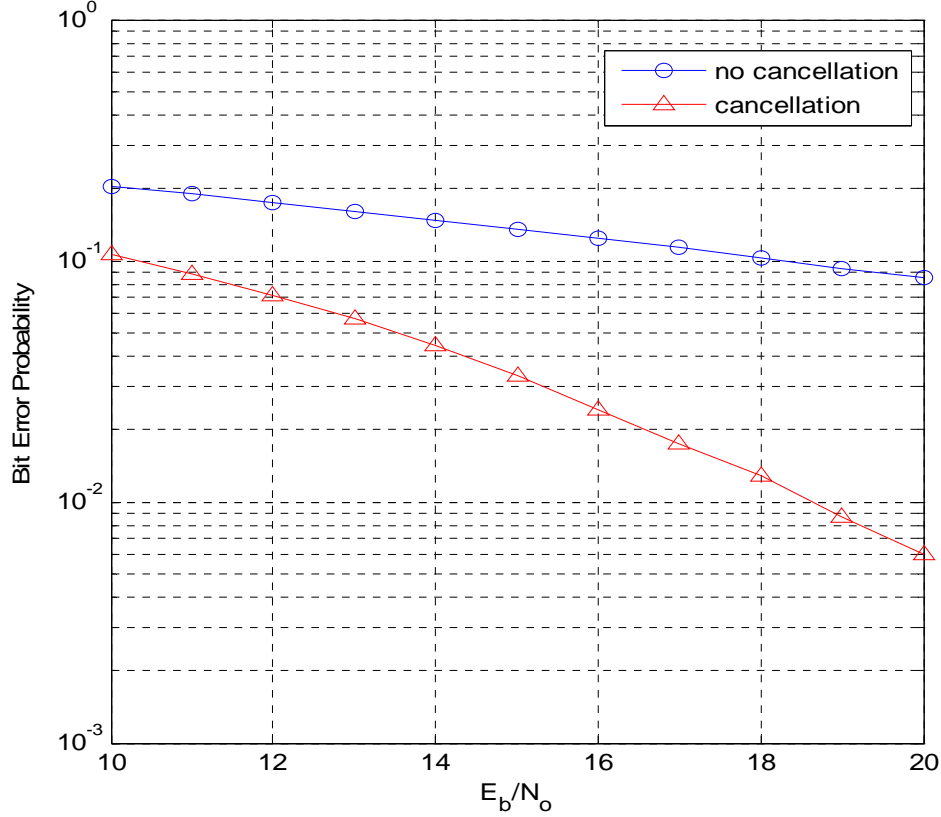
Figure 24.   Cancellation with projection method for 52 effective users.

E. CHAPTER SUMMARY

From the above results, we do not see any improvement for less than 32 effective users, but it seems worthwhile to have a more complex receiver for a large number of effective users. The improvement in channel capacity is obvious for a high capacity system.

In the next chapter, we will examine the performance of the cancellation with modified projection method.

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VI. PERFORMANCE ANALYSIS OF CANCELLATION WITH MODIFIED PROJECTION METHOD

In the modified projection method, the regenerated signal of the first finger $\beta(t)$ is projected onto the orthogonal direction to the received signal $\alpha(t)$ and then subtracted from the received signal $\alpha(t)$. Then the remaining fingers receive the signal $\gamma(t)$:

$$\gamma(t) = \alpha(t) - \frac{\langle \alpha(t), \beta(t) \rangle}{\langle \alpha(t), \alpha(t) \rangle} \bullet \alpha(t) \tag{6.1}$$

where $\langle \alpha, \beta \rangle$ is the inner product of α and β.

In the following paragraphs, we show the results for the modified projection method for different number of effective users, 12, 23, 32, and 52, and compare the performance of our receiver with a conversional Rake receiver that does not use any cancellation techniques.

A.   FOR 12 EFFECTIVE USERS

The performance both with and without cancellation for 12 effective users is shown in Figure 25. As can be seen, the improvement is about 3 dB for $P_b < 5 \times 10^{-4}$.


Figure 25.   Cancellation with modified projection method for 12 effective users.

B.   FOR 26 EFFECTIVE USERS

The performance both with and without cancellation for 26 effective users is shown in Figure 26. As can be seen, the relative improvement is about 0.5 dB for $P_b < 6 \times 10^{-3}$, but the absolute performance is seriously degraded as compared to 12 effective users.

Figure 26.   Cancellation with modified projection method for 26 effective users.

C.   FOR 32 EFFECTIVE USERS

The performance both with and without cancellation for 32 effective users is shown in Figure 27. As can be seen, the relative improvement is about 2 dB at $P_b=10^{-2}$, but the absolute performance is seriously degraded as compared to 12 effective users.
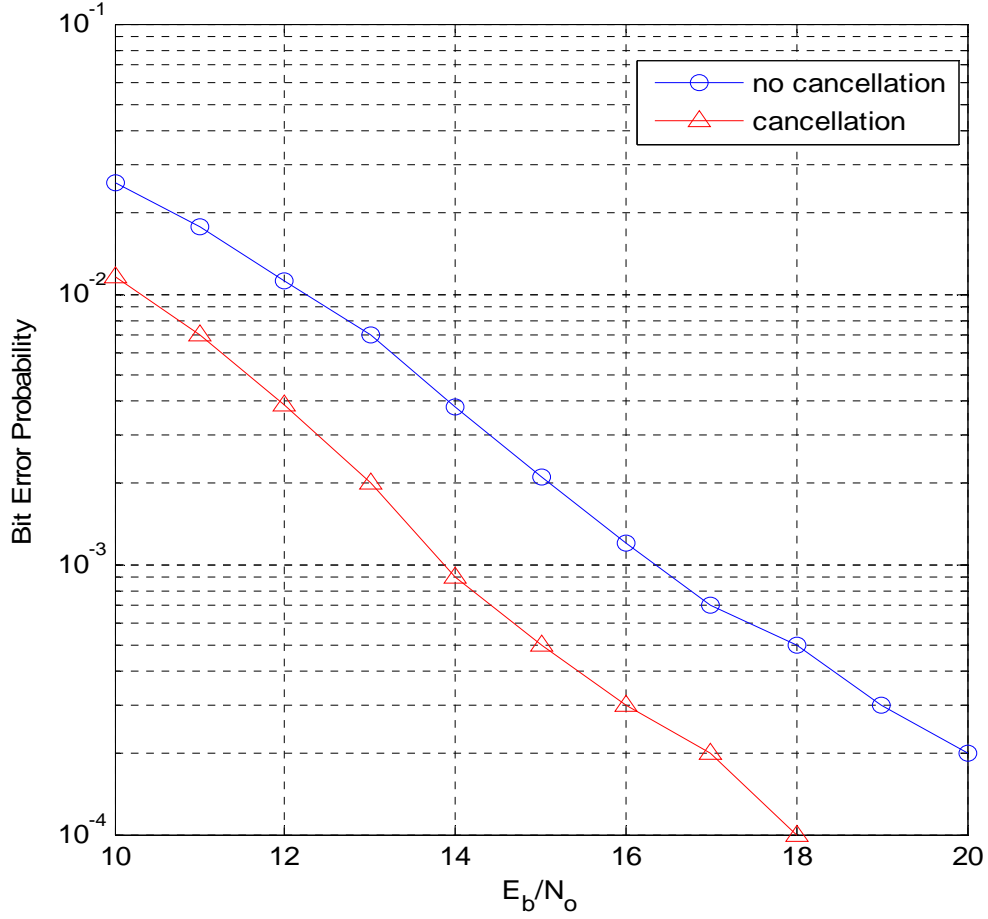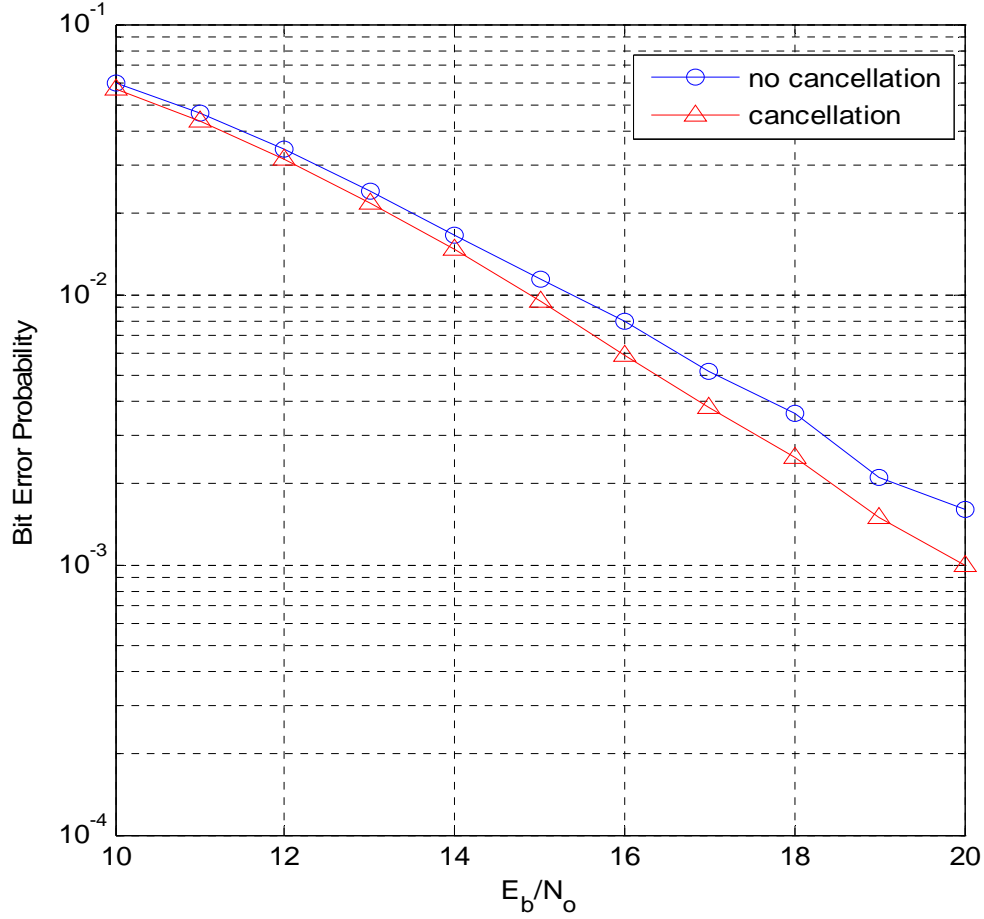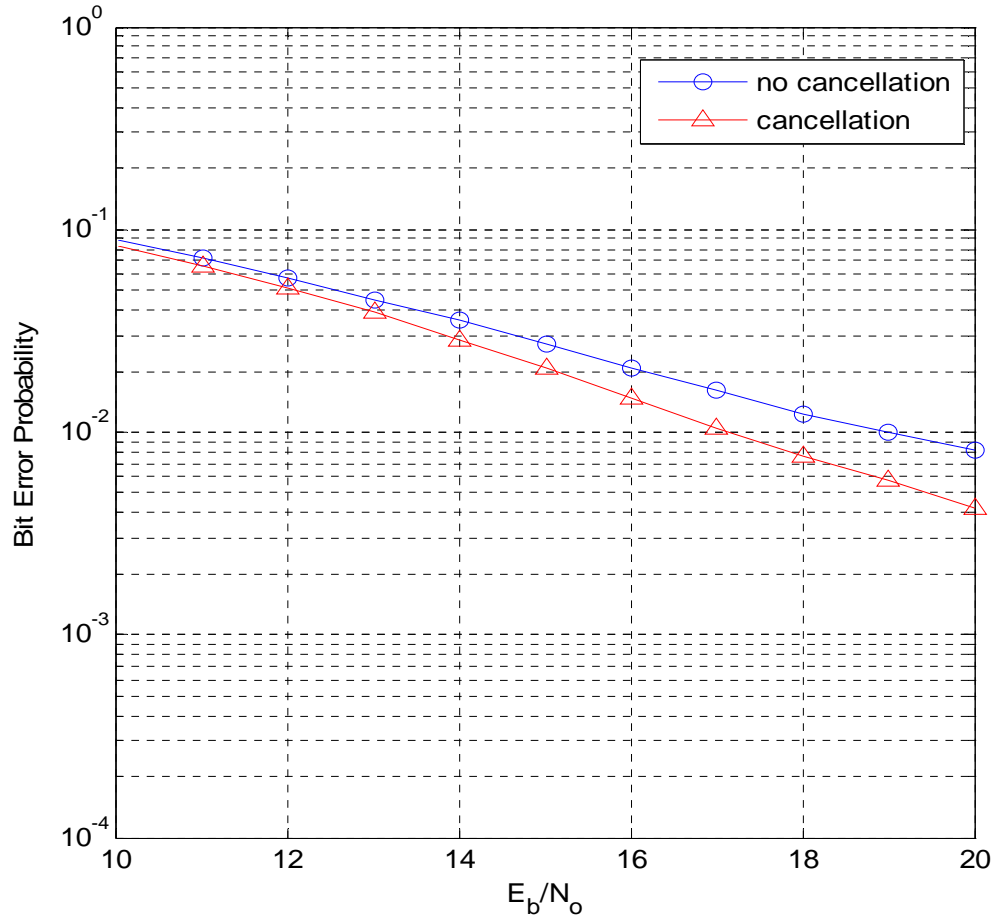

Figure 27.   Cancellation with modified projection method for 32 effective users.

D.   FOR 52 EFFECTIVE USERS

The performance both with and without cancellation for 52 effective users is shown in Figure 28. As can be seen, the relative improvement is about 1 dB at P_b=0.1, but the absolute performance is seriously degraded as compared to smaller numbers of effective users.
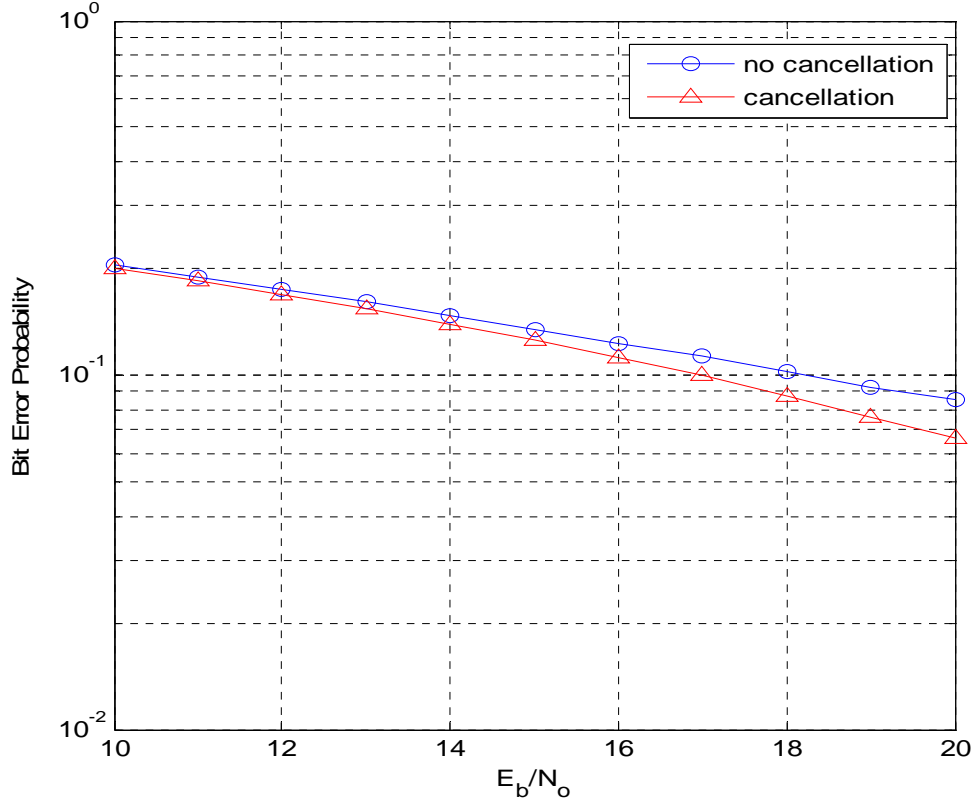

Figure 28.   Cancellation with modified projection method for 52 effective users.

E.   CHAPTER SUMMARY

From the results presented in this chapter, we see a modest improvement in performance with the modified projection method for a large number of effective users.

In the next chapter, we will compare all cancellation methods.

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VII. COMPARISON OF THE PERFORMANCE OF CANCELLATION METHODS

In this chapter, we provide the performance comparison of all methods presented in the previous chapters.

A. FOR 12 EFFECTIVE USERS

The performance for all methods of cancellations and without cancellation for 12 effective users is shown in Figure 29. As can be seen, the best methods are the modified projection and subtraction, with an improvement of about 3 dB and 2 dB, respectively, at $P_b = 2x10^{-4}$.

Figure 29.   Performance comparison for 12 effective users.

B.   FOR 26 EFFECTIVE USERS

The performance for all methods of cancellations and without cancellation for 26 effective users is shown in Figure 30. As can be seen, the best methods are again the modified projection and subtraction with an improvement of 0.5 dB and 1 dB, respectively, at $P_b = 2 \times 10^{-3}$. Note that as the number of effective users is increased, the modified projection method performance is degraded relative to the performance of the subtraction method, but neither method is as effective when the number of effective users is large.
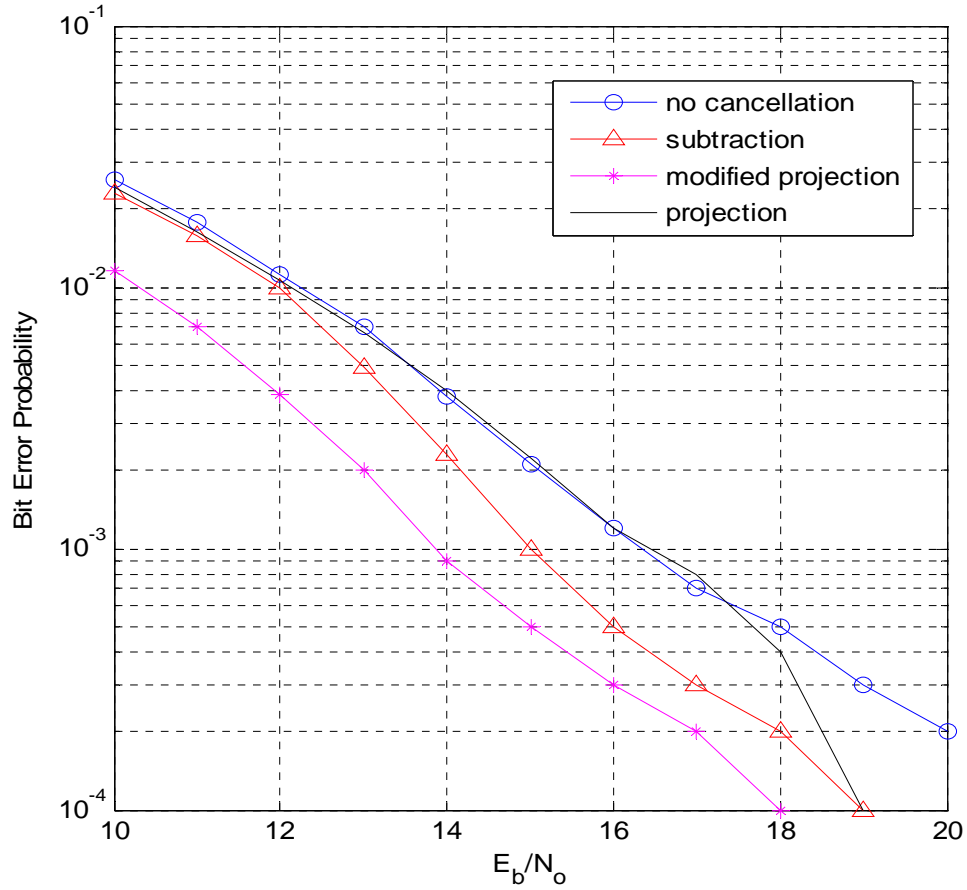

Figure 30.   Performance comparison for 26 effective users.

C. FOR 32 EFFECTIVE USERS

The performance for all methods of cancellations and without cancellation for 32 effective users is shown in Figure 31. We observe that, in this case the best method is projection with an improvement of 4 dB, followed by both subtraction and the modified projection method with an improvement of 2 dB at $P_b = 0.01$.
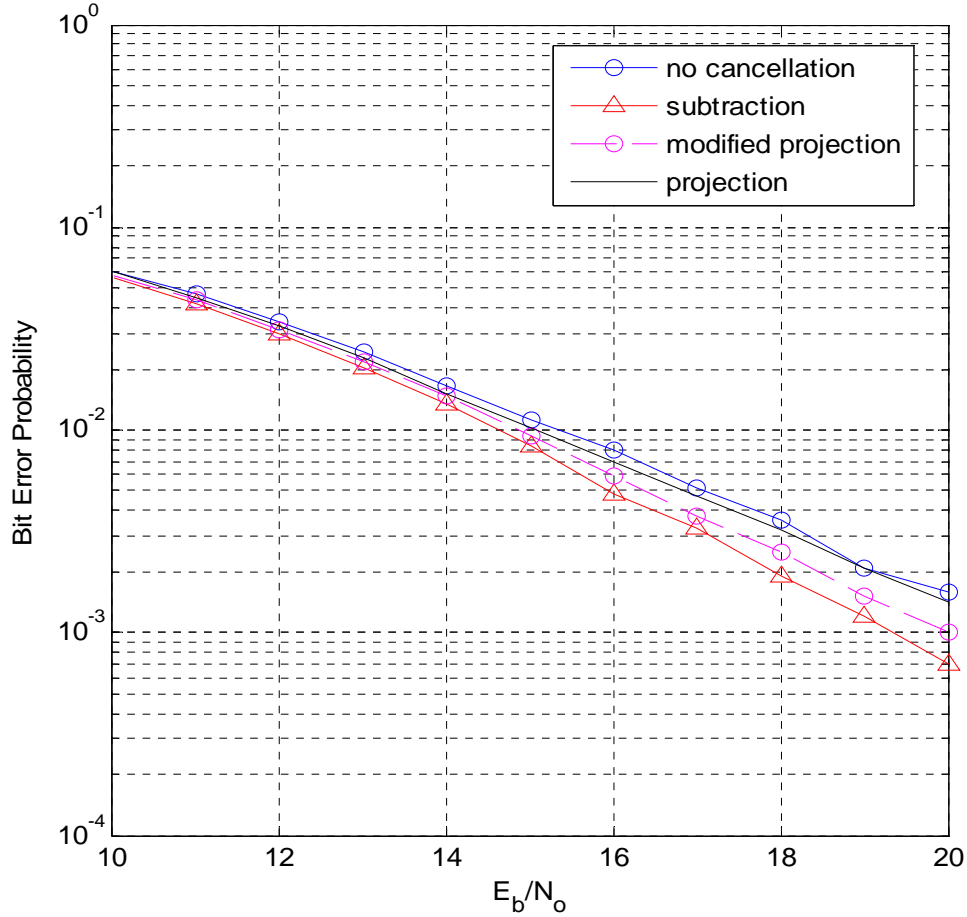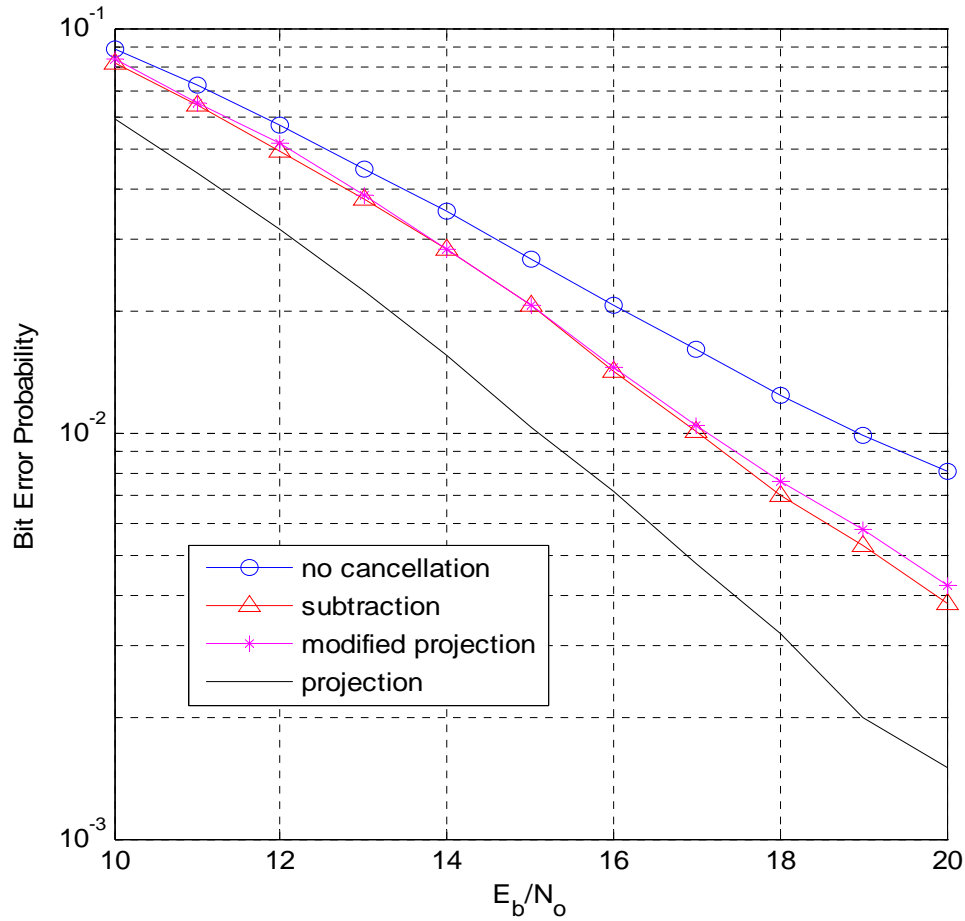

Figure 31. Performance comparison for 32 effective users.

D. FOR 52 EFFECTIVE USERS

The performance for all methods of cancellations and without cancellation for 52 effective users is shown in Figure 32.
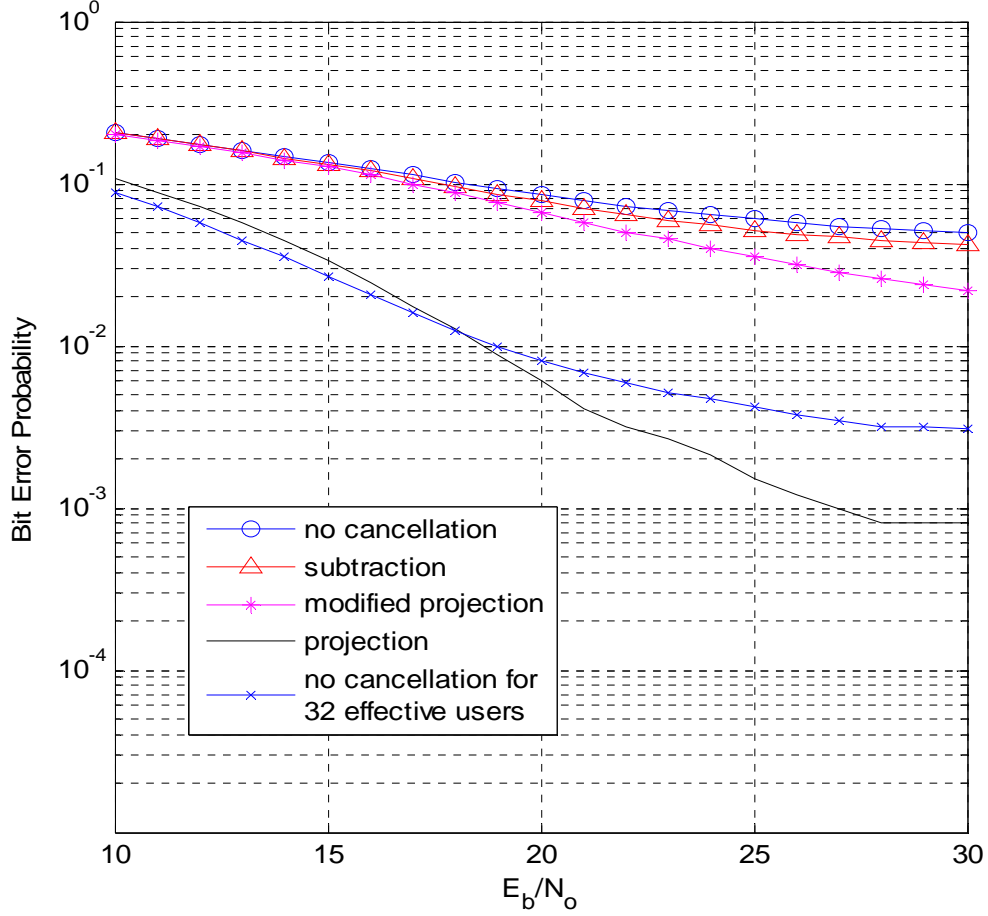

Figure 32.   Performance comparison for 52 effective users.

We observe that the best method for 52 effective users in the projection method. We also notice that the bit error probability for 52 effective users using the projection method is better than that of 32 effective users with no cancellation, resulting in an improvement in throughput of 150%.

E.   CHAPTER SUMMARY

We conclude that is worthwhile to use the projection method for more than 32 effective users to improve the communication system reliability. An adaptive system that employs the subtraction and the modified projection methods for up to 26 effective users, and the projection method for more than 26 effective users can provide superior performance as compared to a system that adapts only one method.

In the next chapter we will examine the performance of Walsh Index Detector that can detect the Walsh indexes that are being used in W-CDMA signals without prior knowledge.

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VIII. PERFORMANCE ANALYSIS OF WALSH INDEX DETECTOR (WID)

In this chapter, we demonstrate a system that can find the Walsh indices that are used by CDMA users. First, we will show the theoretical background that the Walsh Index Detector is based on, and then we demonstrate our experiments.

A.   BACKGROUND THEORY

Our theory is based in linear algebra and the properties of matrices. We assume that we know all the parameters of CDMA modulation except the Walsh indices. In our experiments, we have 7 users, and we aim to find their Walsh indexes which are 14, 38, 49, 52, 80, 104, and 113. The maximum spread factor is 128.

Our detector contains 128 parallel systems, one for every index as shown in Figure 33.
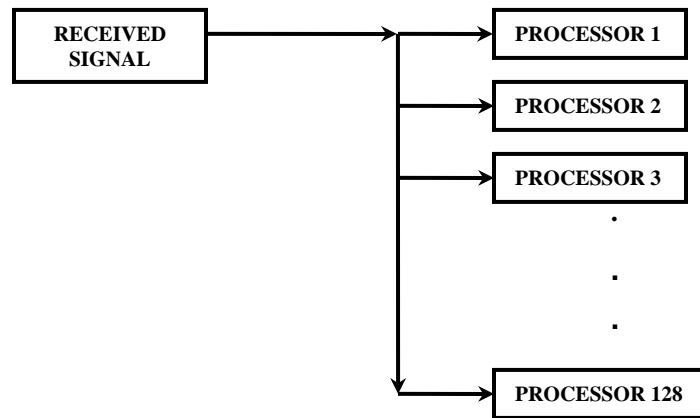

Figure 33.   Concept of a Walsh Index Detector.

In each processor, we multiply the same received signal chips with one specific Walsh function index. For example, processor No. 1 use index No. 1, processor No. 2 use index No. 2, etc. Figure 34 illustrates the process.
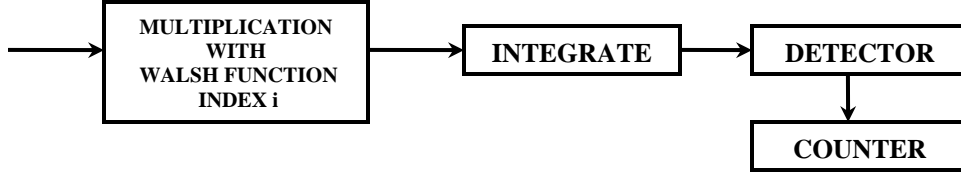
Figure 34.   Concept of processors in WID.

For simplicity of explanation, we use a spread factor equal to four that is produced from the following Hadamard matrix H_4:

$$H_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}. \qquad (8.1)$$

Consider the received signal that contains a user with Walsh index No. 2:

$$A = \begin{bmatrix} 1 & -1 & 1 & -1 \end{bmatrix}. \qquad (8.2)$$

At time t_1 bit 1 is transmitted, so after spreading that bit by multiplication of every chip with 1, the matrix of the spreading signal remains the same:

$$A' = \begin{bmatrix} 1 & -1 & 1 & -1 \end{bmatrix}. \qquad (8.3)$$

Now we take the inner product of that matrix with all possible indices and integrate the chips to obtain: 0 for index No.1, 4 for index No.2, 0 for index No.3, and 0 for index No.4.

Now consider at t_2 bit -1 is transmitted, so after spreading that bit by multiplication of every chip with -1, the matrix of the spreading signal B is:

$$B = \begin{bmatrix} -1 & 1 & -1 & 1 \end{bmatrix}. \qquad (8.4)$$

We follow the preceding steps again and find: 0 for index No.1, -4 for index No.2, 0 for index No.3, and 0 for index No.4.

Now we use a detector that compares the output of the integrator with zero and feed a counter which counts the disagreements.

B.   EXPERIMENTS

In all experiments, we test our Walsh Index Detector for the first 50 bits that are transmitted. We examine our detector in three different environments and show results in two different figures. The first is for the complete spectrum of indices, from 0 to 128, where we can detect the seven indexes 14, 38, 49, 52, 80, 104, and 113 that are used. In the second, we focus on the detection of the first user with index 14.

1.   Ideal Channel

In our first experiment we assume that the channel is ideal, without noise or delay. We can recognize indexes 14, 38, 49, 52, 80, 104, and 113 in Figure 35, and in Figure 36 we show the results from the same experiment focusing only on index No. 14.
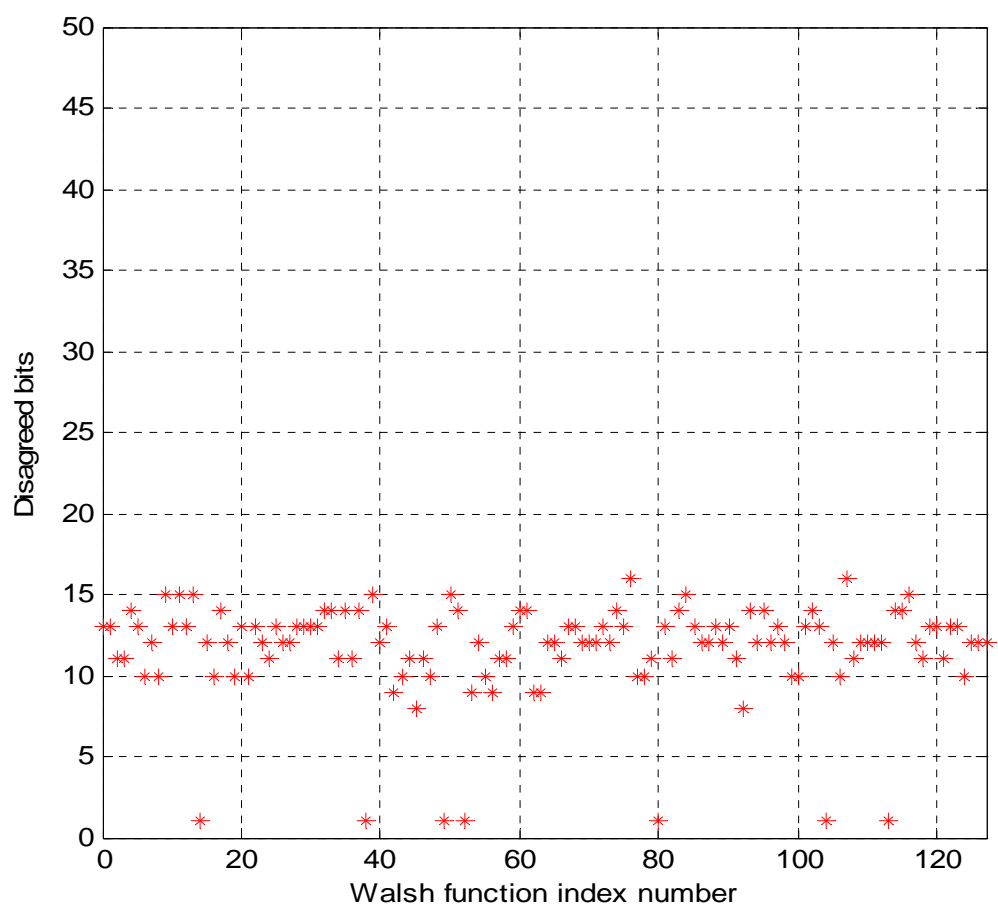
Figure 35.   Walsh index detector for indexes 14, 38, 49, 52, 80, 104, and 113 in a noiseless environment for a spread factor of 128.
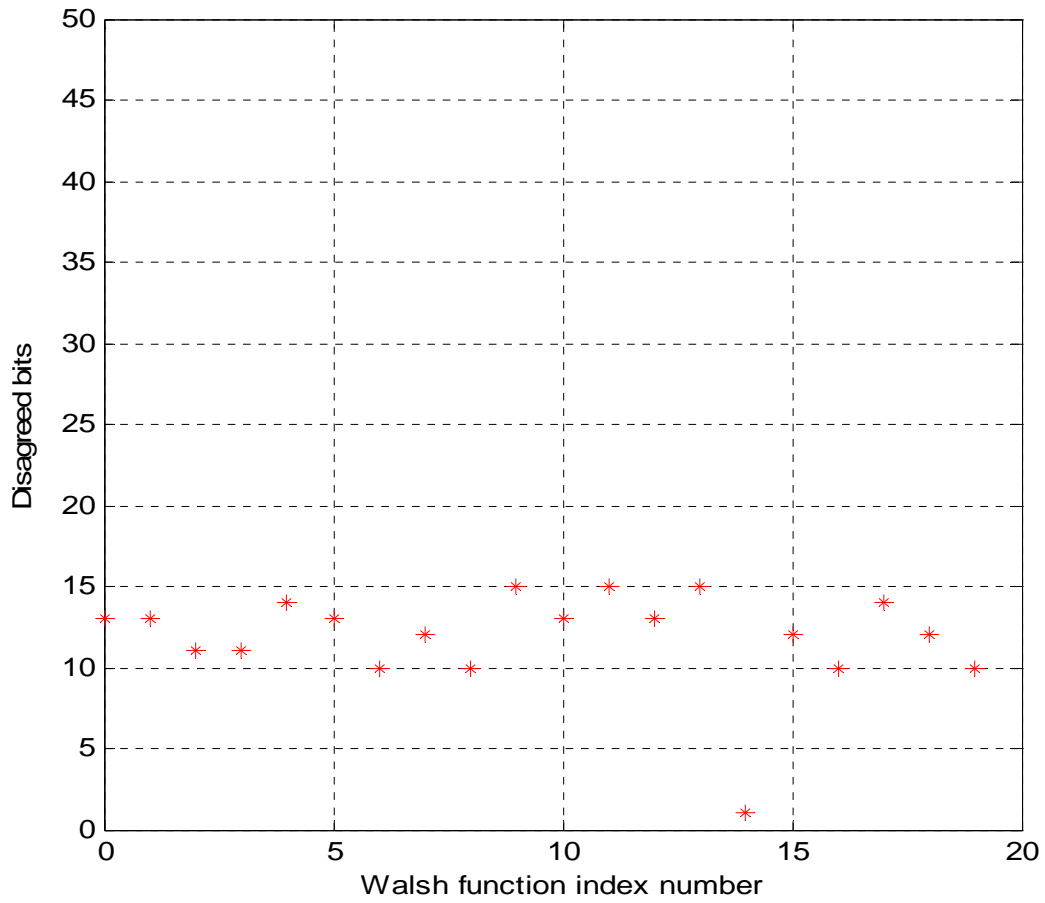
Figure 36.   Walsh index detector for index 14 in a noiseless environment for a spread factor of 128.

2.   AWGN Channel

In this experiment we assume that the channel is a non-fading channel with Signal to Noise Ratio (SNR) equal to 10 dB. Again we can recognize indexes 14, 38, 49, 52, 80, 104, and 113 in Figure 37, and in Figure 38 we show the results from the same experiment focusing only on index No. 14.

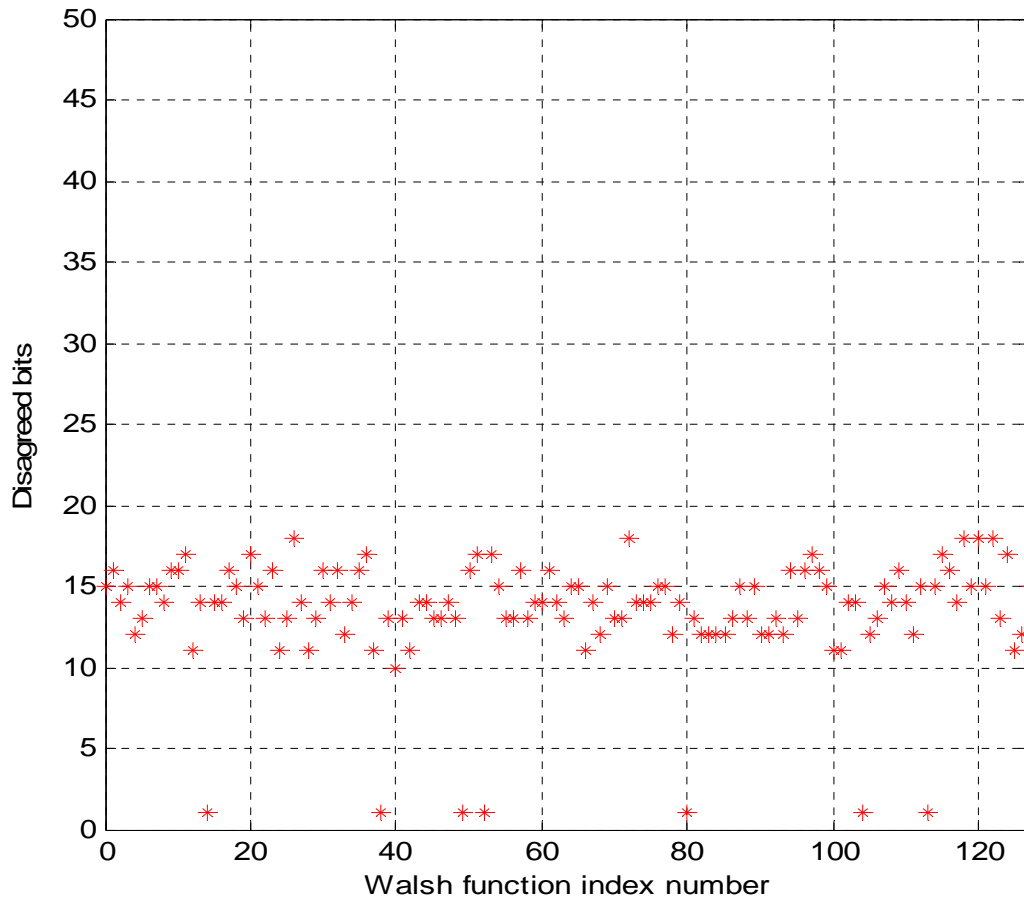Figure 37.   Walsh index detector for indexes 14, 38, 49, 52, 80, 104,   and 113 in an AWGN channel with SNR equal to 10 dB and for a spread factor of 128.

Figure 38.   Walsh index detector for index 14 in an AWGN channel with SNR equal to 10 dB and for a spread factor of 128.

3.   Fading Channel

In this experiment we assume that the channel is a fading channel. The SNR is 10 dB. We use the same characteristics for the fading channel as in Chapter III. We can recognize indices 14, 38, 49, 52, 80, 104, and 113 in Figure 39, and in Figure 40 we show the results from the same experiments focusing only on index No. 14.
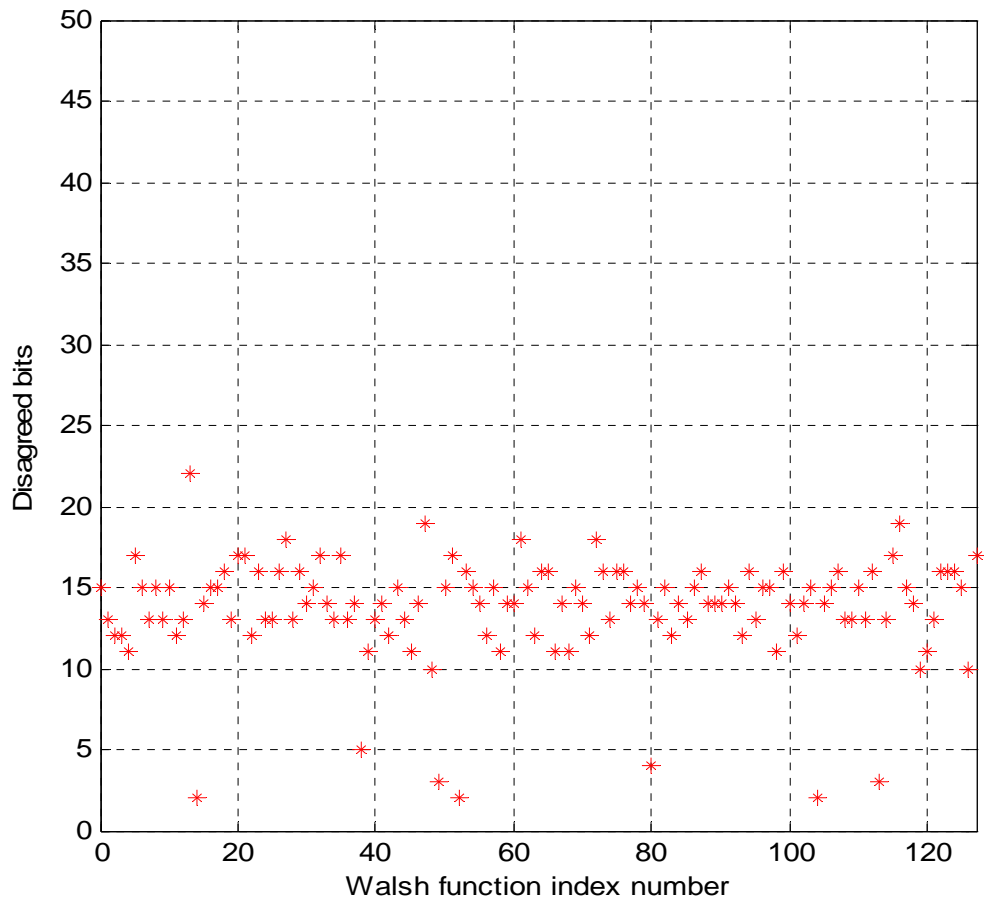
Figure 39.   Walsh index detector for indexes 14, 38, 49, 52, 80, 104,   and 113 in a fading
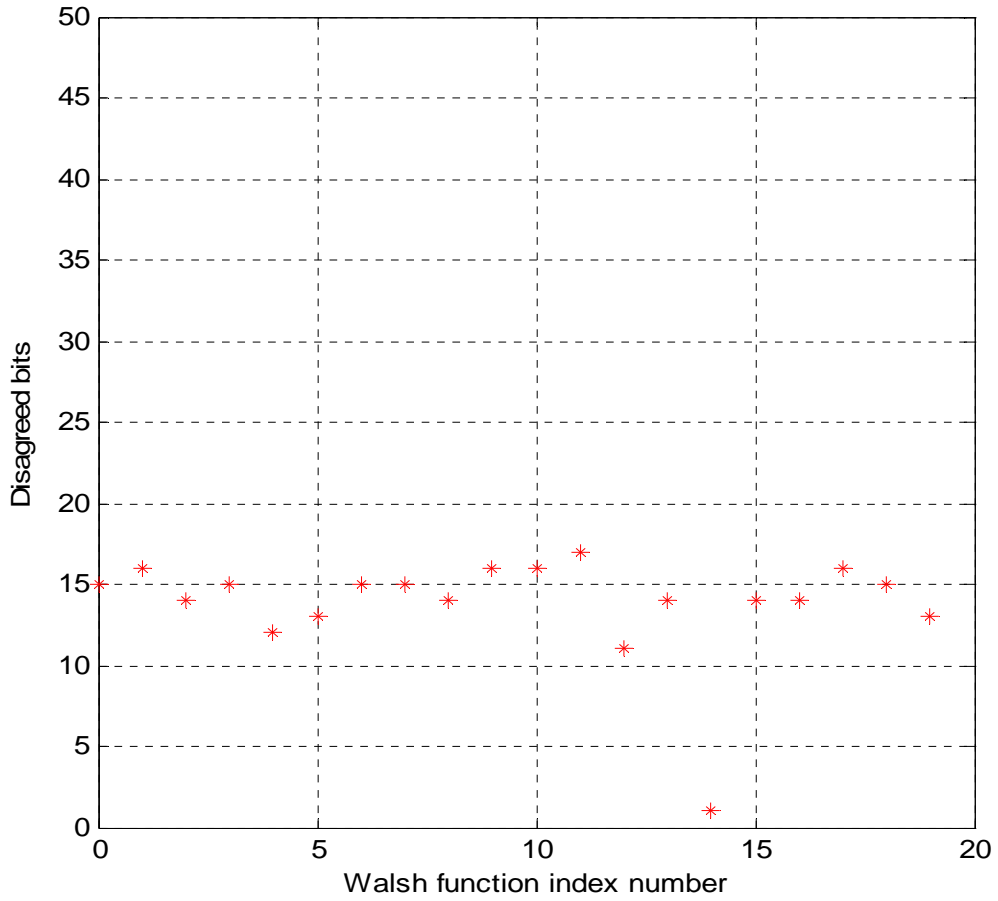environment with SNR equal to 10 dB and for a spread factor of 128.
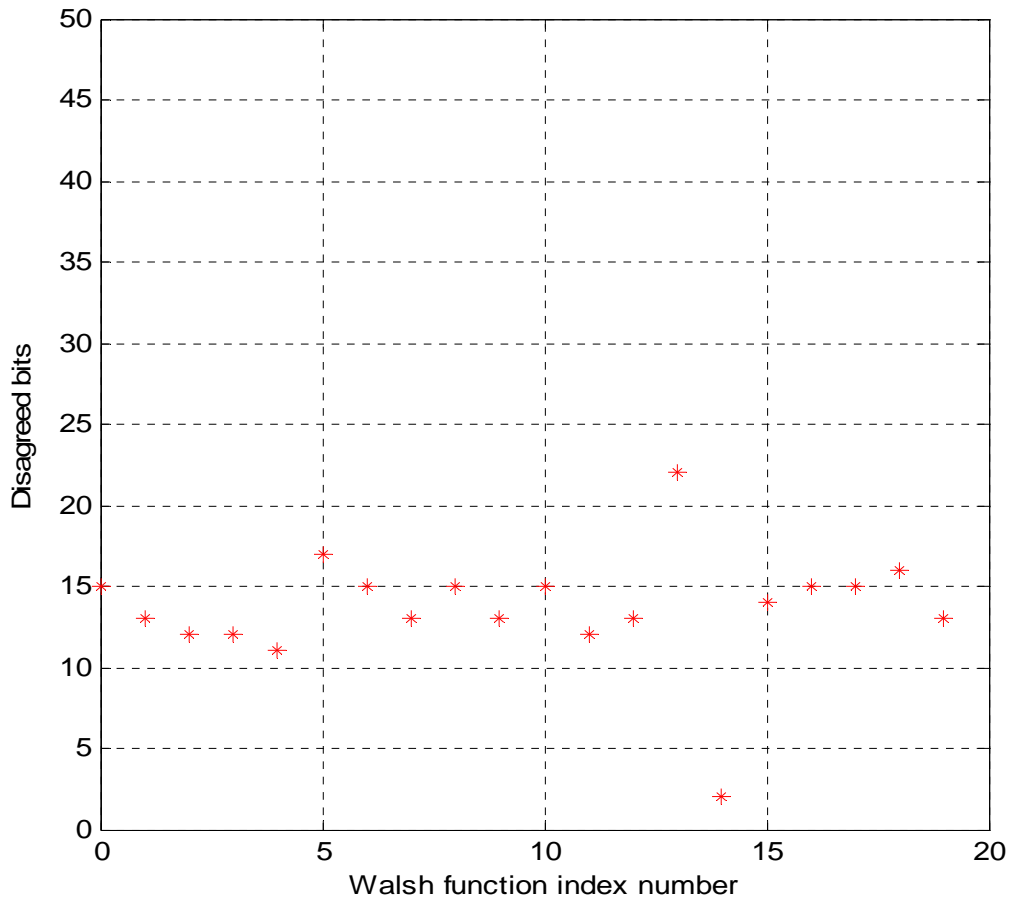
Figure 40.   Walsh index detector for index 14 in an in a fading environment with SNR equal to 10 dB and for a spread factor of 128.

C.   CHAPTER SUMMARY

In Figures 41 and 42 we combine all the preceding results from this chapter in order to compare performance in the three different environments. The WID works appropriately in all cases.
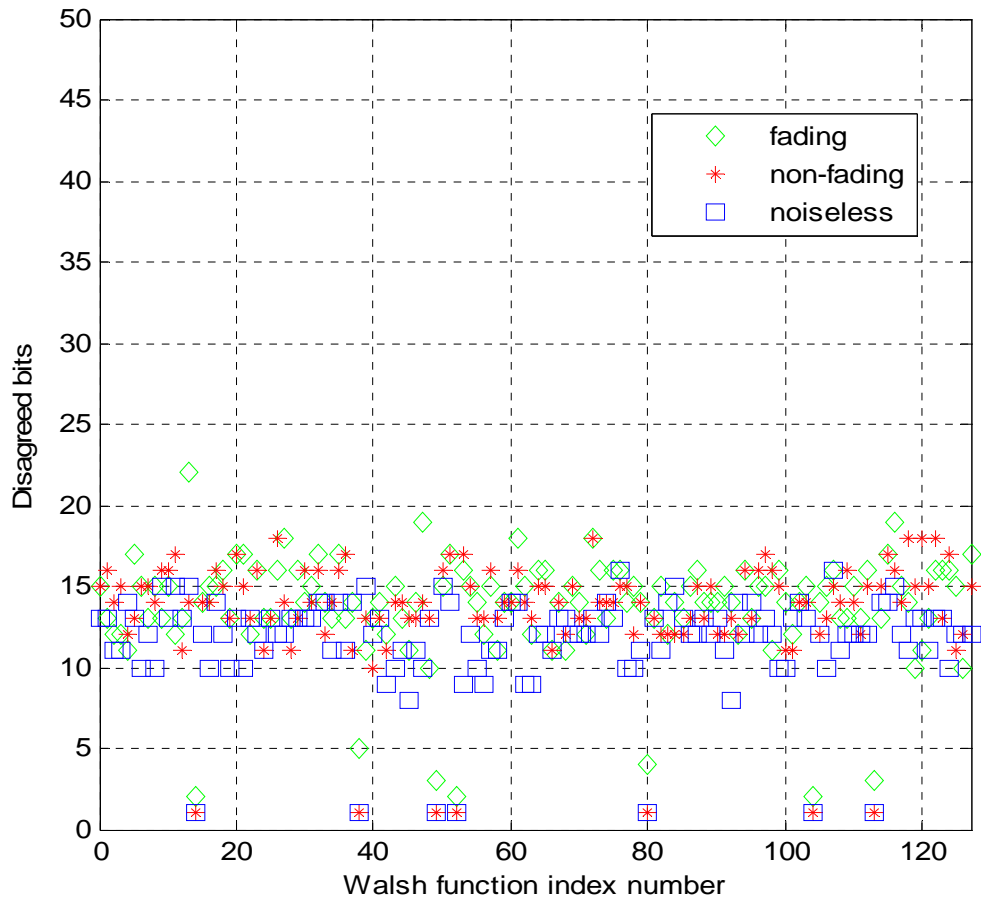
Figure 41.   Comparison of Walsh index detector between non-fading, fading and noiseless channels for indexes 14, 38, 49, 52, 80, 104 and 113 for a spread factor of 128.

Figure 42.   Comparison of Walsh index detector for index 14 between non-fading, fading
and noiseless channels for a spread factor of 128.

In the next chapter, we summarize the conclusions of the thesis and make recommendations for future work.

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IX. CONCLUSION AND FUTURE WORK

A. CONCLUSION

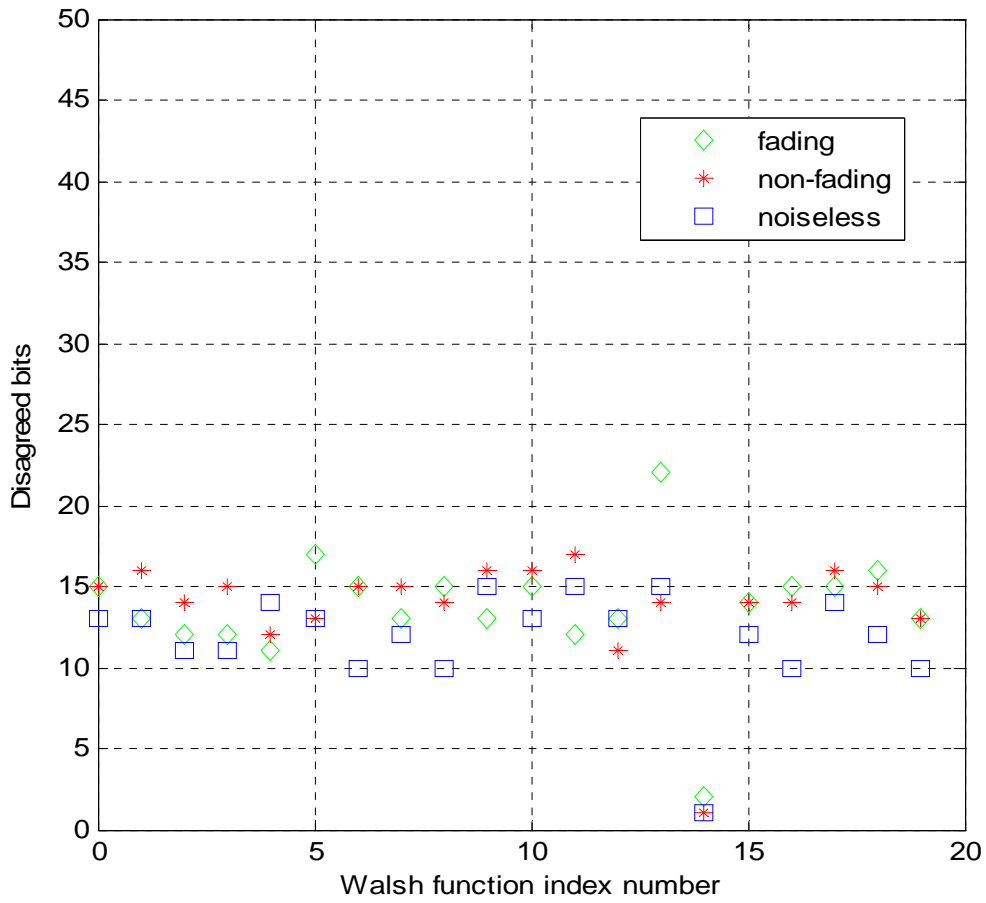This research focused on the CDMA forward link (downlink) where orthogonal covering is employed. The main point of our research was to create an original modified Rake receiver to decrease Intracell Interference and increase the capacity of the channel.

In our research instead of canceling out the stronger user one by one [1], we cancel out the stronger finger output from the signals of all users simultaneously.

Based on reference [1] we examined two interference cancellation techniques to suppress intracell multiuser interference, *subtraction* and *projection*. We also examine a new original method, *modified projection method,* where the regenerated signal of the first finger is projected onto the orthogonal direction to the received signal and then subtracted from the received signal.

We found that it is worthwhile to use the projection method when more than 32 effective users are transmitting. With that method we can achieve an improvement of 150% in channel capacity. The subtraction and modified projection methods work better than the projection method when the number of effective users transmitting is smaller than twenty-six.

We conclude that an adaptive system that can combine all three methods can provide superior performance across a large range of effective users.

Based in linear algebra and the properties of matrices we create an original new detector that can find all the indices that are being used in CDMA signal without prior knowledge of them. We provide the theoretical background and examine the performance of Walsh Index Detector (WID) in three different environments and we show that works appropriately in all cases.

B. FUTURE RESEARCH AREAS

The area of interference cancellation for cellular communications will be a subject of intense research in the future as the need for more capacity increases.

The projection method is best for high data rates. One subject for future research is how to subtract the interference in all signals by comparing the received stronger signals with the regenerated ideal signals. Moreover, we may calculate the exact characteristics of the paths and regenerate the weaker signals with the final target of eliminating all interference.

Another area of research is the use of Walsh Index Detector in hand off methods between cells, so as to detect and distinguish users. Also we can use the same benefit in cell sectoring and in microcells where the users change stations very often.

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